



Proceedings

2018 ASPE and euspen Summer Topical Meeting

Advancing Precision in Additive Manufacturing

July 22-25, 2018

American Society for
Precision Engineering

P.O. Box 10826, Raleigh, NC 27605-0826
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Proceedings of
2018 Summer Topical Meeting
on
Advancing Precision in Additive Manufacturing

July 22-25, 2018

**Lawrence Berkeley National Laboratory
Berkeley, California, USA**

The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.

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Preface

This book comprises the proceedings of the 2018 Summer Topical Meeting, *Advancing Precision in Additive Manufacturing*. The contributions reflect the authors' opinions and are published as presented to ASPE without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE or its editorial staff.

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Foreword

Dear Meeting Delegates,

Welcome to ASPE and euspen's 2019 topical meeting on dimensional accuracy and surface finish in additive manufacturing: *Advancing Precision in Additive Manufacturing*. We are a jointly sponsored euspen Special Interest Group and ASPE Topical Meeting, alternating across the Atlantic. This is the 5th meeting in the series, where last year we met in Leuven, Belgium, this year in Berkeley, California, with a return to Europe in 2019.

What sets our meeting apart from the plethora of other meetings on additive manufacturing (AM) is our proactive and conscious commitment to *determinism* and expertise in *precision engineering*. We might summarize our creed of determinism as the commitment to *ensuring results with high certainty* by 1) a first-principles understanding of performance and error sources; 2) pursuit of repeatability; 3) expressing performance using quantifiable metrics; and 4) the ability to measure and often control these quantifiable metrics. Our precision engineering expertise embodies many tools including error budgets, statements of uncertainty, system modelling, standards, controls, etc. to meet the demands of determinism.

As we meet here in Berkeley, the span of papers strives to improve determinism in AM. We have papers on the physics of material and surface formation and the dependence of errors on process variables. We examine the in-process controls needed to achieve predictable and repeatable results. We strive to relate quality with specifiable and measurable quantities and consider standards as necessary tools for ensuring predictable product quality. And we develop metrology tools for characterizing volumes and surfaces with unique challenges. We are also seeking a greater focus on metallurgy and fatigue, not to compete with other conferences dedicated to these topics, but to acknowledge their importance in meeting functional requirements for components such as precision flexure elements.

We ask all of the listeners and speakers to consider how their topics and presentations contribute to determinism. Please take the explicit and proactive step in answering *how does this work push additive manufacturing forward as a deterministic manufacturing process?* Are we specifying and measuring the right things? Are we using the most appropriate measurement tools? Are we rigorous about our treatment of measurement uncertainties?

Above all, let's work together to make this meeting useful. We need to leave Berkeley with action items of what we will do better based on our shared experiences. And, of course, let's share our comradeship in precision engineering!

Co-Chairs

John S. Taylor, University of North Carolina – Charlotte
Richard K. Leach, University of Nottingham, UK

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Sam Anand, University of Cincinnati
David J. Bate, Nikon Metrology
Marcin B. Bauza, Carl Zeiss Industrial Metrology
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Brett Griffith, Honeywell – National Security Campus
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Ola L. A. Harrysson, North Carolina State University
Bradley H. Jared, Sandia National Laboratory
Wayne E. King, Lawrence Livermore National Laboratory
Michael M. Kirka, Oak Ridge National Laboratory
Shan Lou, University of Huddersfield
Stephen J. Ludwick, Aerotech, Inc.
Robert M. Panas, Lawrence Livermore National Laboratory
David Bue Pedersen, Technical University of Denmark
Antonius T. Peijnenburg, VDL Enabling Technologies Group
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Kirk Rogers, GE Additive Customer Experience Center
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Meeting Program

Sunday, July 22, 2018

9:00 AM – 12:00 Noon – Tutorial

Basics of Metrology

Richard Leach (University of Nottingham, UK)

8:00 AM – 12:00 Noon – Tutorial

Fracture and Fatigue Issues for (Metal) Additive Manufacturing

John J Lewandowski – Arthur P Armington Professor of Engineering II and Director Advanced Manufacturing and Mechanical Reliability Center (AMMRC), Case Western Reserve University, Cleveland, OH

12:00 Noon – 1:00 PM – Lunch on-your-on

1:00 PM – 5:00 PM – Tutorial

X-ray Computed Tomography for Dimensional Metrology

Adam Thompson (University of Nottingham); Massimiliano Ferrucci (Materialise);
Evelina Ametova – (KU Leuven)

1:00 PM – 5:00 PM – Tutorial

Applications of Metal Additive Manufacturing to Precision

Kevin Raedts (VDL ETG); Gerrit Oosterhuis (VDL ETG)

6:30 PM – Welcome Reception at Jupiter – 2181 Shattuck Ave, Berkeley, CA 94704

Monday, July 23, 2018

8:00 AM – Registration & Light Breakfast

8:30 AM – Conference Opening

Welcome

Eric Buice, ASPE President, Lawrence Berkeley National Laboratory

Opening Remarks

John S. Taylor, Conference Co-chair, University of North Carolina-Charlotte

Perspective

Richard K. Leach, Conference Co-chair, University of Nottingham
David Bue Pedersen, Technical University of Denmark

Keynote Speaker

Precision Additive Metal Manufacturing

Ann Witvrouw (University of Leuven (KU Leuven))

9:45 AM – Session 1: Applications of AM & Functional Specifications

Antonius T. Peijnenburg (VDL Enabling Technologies Group) and
Sam Anand (University of Cincinnati)

Oral Presentation

**Precise Additive Manufacturing Technology Application to Heavy Duty
Industrial Gas Turbines**

Vogel, G.; Rosenbarger, T.; McNally, J.; Houck, L. (Power Systems Manufacturing) 1

Oral Presentation

Design and Evaluation of a 3D Printed Flexure for a Fast Steering Mirror

Schlarp, J.; Csencsics, E.; Ito, S.; Schitter, G. (Vienna University of Technology) 7

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Internal Surface Topography and Dimensional Metrology of Microwave Guide using X-ray CT

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Hamann, C.; Kirby, M. (Renishaw Canada Solutions Center) 12

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Eric S. Buice (Lawrence Berkeley National Laboratory) and
John S. Taylor (University of North Carolina-Charlotte)

Carl Zeiss Industrial Metrology

Christoph Graf vom Hagen

Zygo Corporation

Kevin Bowes

Aerotech

William S. Land II

Nikon Metrology

David J. Bate

1:00 PM – Lunch

2:25 PM – Session 3: Design for Manufacturing

Gerrit Oosterhuis (VDL Enabling Technologies) and
Bradley H. Jared (Sandia National Laboratories)

Keynote Speaker

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Oral Presentation

Topology Optimization for Additive Manufacturing: Fully Printable Compliant Mechanisms

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R. (Netherlands Aerospace Centre) 40

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Simulation Assisted Design for an Additively Manufactured Autoclave

Tool Accounting for an Anisotropic Expansion

Kim, S.; Hassen, A. A.; Lindahl, J.; Post, B.; Love, L. E.;
Kunc, V. (Oak Ridge National Laboratory) No abstract

4:00 PM – Session 4: Lattice & Thin Sections

Michael M. Kirka (Oak Ridge National Laboratory) and
David Bue Pedersen (Technical University of Denmark)

Oral Presentation

Micro Powder Bed Fusion (μ -PBF) – Extremely High Resolution for Small-scale Applications

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Adapted Scan Strategy and Slicing Tool for Improvement of Strut Precision in Lattice Structures

Korn, H.; Kordaß, R.; Müller, B. (Fraunhofer Institute for Machine Tools and
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Stelzer, R. (Technische Universität Dresden) 50

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Davoudinejad, A.; Diaz Perez, L. C.; Quagliottia, D.; Pedersen, D. B.;
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Yagüe-Fabra, J. A. (University of Zaragoza) 55

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Chen, S.-C. (The Chinese University of Hong Kong) 60

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Wu, Z.; Narra, S. P.; Subedi, S.; Beuth, J. (Carnegie Mellon University) No abstract

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Characterisation of the Influence of the Colour in Resin for Micro Parts Production by Photopolymerization Based Additive Manufacturing System

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Seno Rekawa (Lawrence Berkeley National Laboratory) and
Pete J. Fitsos (Lawrence Livermore National Laboratory)

6:00 PM – Travel to Dinner Location at Skates – 100 Seawall Dr, Berkeley, CA 94710

6:30 PM – Cocktail Hour & Dinner at Skates

10:30 PM – Travel to Hotels

Tuesday, July 24, 2018

8:00 AM

Registration & Light Breakfast

8:30 AM

Welcome & Announcements

John S. Taylor (University of North Carolina-Charlotte)
and Richard K. Leach (University of Nottingham)

8:40 AM – Session 6: Standards

Jason C. Fox (National Institute of Standards & Technology) and
Sam Anand (University of Cincinnati)

Oral Presentation

ISO 10360 pt 11: Progress Towards an XCT Verification Standard

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Richard K. Leach (University of Nottingham) and
Kirk Rogers (GE Additive Customer Experience Center)

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Kimm, M.; Schueckler, P.; Schoenen, D.; Corves, B. (RWTH Aachen University);
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**Holistic View of the Mechanical Performance of Metals Fabricated
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Kirka, M. M. (Oak Ridge National Laboratory) No abstract

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**Fatigue Behavior of Surface Treated Ti-6Al-4V Made via Electron Beam
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2:45 PM – Session 9: Subsurface Defect Measurements

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Shan Lou (University of Huddersfield)

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Correlating Volume and Surface Features in Additively Manufactured Metal Parts

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Senin, N. (University of Nottingham and University of Perugia) 116

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**Detection of Subsurface Defect for Metal Additive Manufacturing
Using Flash Thermography**

Zhang, B.; Duemmler, M.; Davies, A.; Ziegert,
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**In-situ Detection of Porosity and its Correlation with Fatigue Behavior
of Additive Manufactured Ti-6Al-4V**

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Dehoff, R. R. (Oak Ridge National Laboratory). No abstract

Poster Presentation

**Effect of Subsurface Defects on the Surface Topography
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Seno Rekawa (Lawrence Berkeley National Laboratory) and
Pete J. Fitsos (Lawrence Livermore National Laboratory)

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David J. Bate (Nikon Metrology)
Ann Witvrouw (University of Leuven (KU Leuven))

Oral Presentation

A Review of AM Artifact Design Methods

Toguem, S. C. T.; Mehdi-Souzani,
C.; Anwer, N. (LURPA, ENS Cachan Univ. Paris-Sud, Université Paris-Saclay);
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Stephen J. Ludwick (Aerotech, Inc.) and
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Hafkamp, T.; de Jager, B.; Etman, P. (Eindhoven University of Technology);
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Cola, M. J.; Beckett, D. P.; Brennen, M. A.; Betts, S. B. (Sigma Labs, Inc.);
Madigan, R. B. (Montana Technical University) No abstract

Poster Presentation

A Beam Modulator and Galvanometer Controller for Metal Powder Bed Fusion

Andersen, S. A.; Del Rio, S.; Pedersen, D. B.;

Hansen, H. N. (Technical University of Denmark) 172

6:40 PM – Dinner on-your-own

Wednesday, July 25, 2018

8:00 AM

Registration & Light Breakfast

8:30 AM

Welcome & Announcements

John S. Taylor (University of North Carolina-Charlotte) and

Richard K. Leach (University of Nottingham)

8:40 AM – Session 13: Surface Characterization

John S. Taylor (University of North Carolina-Charlotte) and

Adam Thompson (University of Nottingham)

Keynote Speaker

**Metal Additive Manufacturing: From the Generation of Surfaces
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**Evolution of Cooling Length in Parts Created Through Laser Powder
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Reese, Z.; Evans, C. J. (University of North Carolina-Charlotte) 195

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10:45 AM – Session 14: CT Measurements

Christoph Graf vom Hagen (Carl Zeiss Industrial Metrology) and

Richard K. Leach (University of Nottingham)

Oral Presentation

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Jason C. Fox (National Institute of Standards & Technology) and
Christopher J. Evans (University of North Carolina-Charlotte)

Oral Presentation

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How Laser Scanning Confocal Microscopy Benefits 3D Printing

Hong, M.; Meng, G. (Olympus Corporation of the Americas) 238

Poster Presentation

Digital Diffractive-Confocal Imaging Correlation Microscopy for Additively Manufactured Surfaces

Chen, L-C.; Wu, E. (National Taiwan University). No abstract

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Bradley H. Jared (Sandia National Laboratories) and
David Bue Pedersen (Technical University of Denmark)

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3:40 PM – Session 17: Powder Control & Properties

Antonius T. Peijnenburg (VDL Enabling Technologies Group) and
Ola L. A. Harrysson (North Carolina State University)

Oral Presentation

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Technical Papers

Precise Additive Manufacturing Technology Application to Heavy Duty Industrial Gas Turbines

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ABSTRACT

This paper is intended to provide information on the analysis and controls of an additive manufacturing process used by Power Systems Manufacturing (PSM) for the fabrication of heavy duty industrial turbine hardware.

Precipitation strengthened Nickel alloys are extensively used in turbomachinery applications thanks to their excellent mechanical capabilities in high temperature environments. However, for the extreme temperatures at which modern gas turbines are operating, even Nickel based super alloys may be unable to meet durability requirements without the use active cooling methods. Since these cooling systems are typically fed with air extracted from the compressor, optimization of cooling efficiency is a commonly studied subject. These studies are often focused on two distinct categories of features:

- 1) Internal cooling features, such as turbulators to enhance heat transfer, or impingement cooling
- 2) External cooling features, such as film cooling generated by cooling air exiting rows of holes.

Up until recently, the geometry of these features has been limited to designs achievable by conventional machining and casting processes. Today, additive manufacturing allows designers to create cooling features that would have been impossible to realize with conventional machining methods.

As with any manufacturing process, deviations from design intent are inevitable and must be accounted for. This paper will focus on manufacturing results of a Laser Powder Bed Fusion (LPBF) process developed specifically for a cooled turbine airfoil with both internal and external cooling features.

MATERIAL PROPERTIES

One of PSM's early business developments was focused on the repair of industrial gas turbine

components, mainly turbine vanes and blades from the hottest sections. These components made of super alloys by the OEM often showed excessive distress, which made the earlier repair process challenging. While repairing a large amount of sets, PSM gained valuable material knowledge related to weldability of super alloys. Since 2006 PSM has been using a proprietary Nickel base super alloy to manufacture turbine hardware. This alloy was designed with a focus on improved weldability in order to replace traditional cobalt alloys that were easier to weld repair but had lower strength and were more prone to cracking.

Since additive manufacturing through Laser Powder Bed Fusion is similar to a precise laser welding process, it was logical for PSM to start development by using the aforementioned alloy in a powdered form. After all, the major element of a successful additive manufactured part resides in its powder composition itself.

Other key elements for successful and precise additive manufacturing builds are the machine laser parameters, which are intrinsically related to the powder composition as well.



Figure 1: Example of DOE coupons build for different laser power and speed levels.

Over the years, PSM conducted several tests with multiple additive machines of different manufacturers such as SLM Solutions™ and EOS™. These tests were performed with the PSM proprietary powder while different laser power levels and speed were applied in order to optimize the resulting material structure. Figure 1 shows the result of a DOE from one machine with independent variables:

- Laser power
- Hatch spacing
- Speed

These are combined together as the so-called "Energy Density" parameter.

Each coupon is typically evaluated for porosity, with the goal of achieving the lowest level possible while maintaining the fastest laser speed and lowest energy to minimize manufacturing cost.

Figure 2, below, shows typical results obtained from this type of DOE with picture #1 and 2 showing non acceptable and acceptable porosity levels respectively. For reference, conventional casting porosity limits are in the range of 2%, whereas the LPBF process easily achieved 10 times less.

Note that due to the improved weldability of the proprietary Nickel-based alloy used by PSM, very low porosity levels were achieved with relatively low energy density compared to other additive manufacturing powders available on the market. This means that the powder used by PSM is more cost effective since allowing faster laser speed and less laser energy.

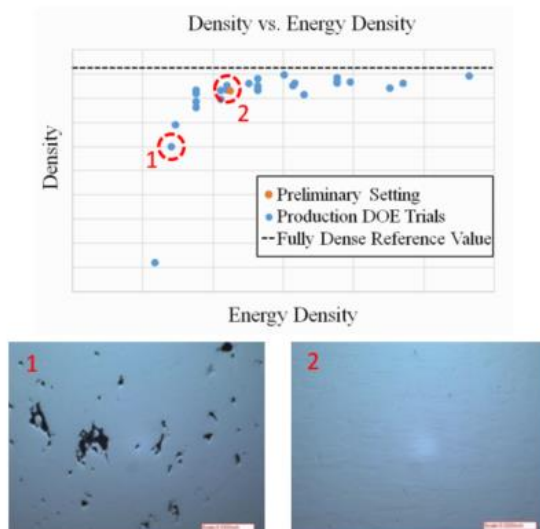


Figure 2; Typical DOE results for Porosity fct of Energy Density levels

Once the optimal core parameters were identified, further tuning of the laser contouring parameters was required in order to achieve the desired feature resolution. Laser speed and power settings need to be adjusted based on the composition of the substrate. As described in Figure 3, the surfaces from a build part that are facing up relative to the build direction are called up-skin surfaces, whereas the ones facing down relative to the build directions are called down-skin surfaces. In the latter situation, it is required for the laser to significantly reduce its energy density in order to avoid accidentally fusing lower powder layers.

Special coupons with key features were built with variable laser settings and evaluated for their overall level of geometrical accuracy and surface roughness. The settings which yielded the coupon with the least amount of roughness on up-skin, vertical, and down-skin surfaces were then picked.

Figure 3 shows one of the geometry features used to evaluate optimal laser settings for best feature resolution. The edge of the surface is supposed to represent a perfect cylinder. Edges of up-skin and vertical surfaces typically achieve relatively precise geometry. Edges of down-skin surfaces, on the other hand, always achieve worse geometry resolution due to the inherent build direction and layer process.

It is worth noting that typical layer thickness used with these Nickel based super alloy powders are in the range of 40 microns. By comparison, powder particle average diameters are in a smaller but similar range.

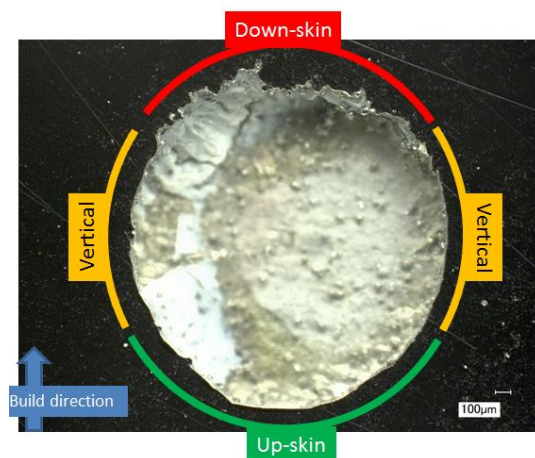


Figure 3: Microscopic view of one of the geometry feature used to define optimum laser parameters during different layers situations.

It is possible that in the future, new technologies such as finer powder and thinner build layers may improve the down-skin geometry situation, but none of these are readily available at the moment.

Therefore it is best to acknowledge this “weakness” and take it into consideration when using LPBF in manufacturing. Methods to compensate for this process deficit are described in the internal geometry precision chapter of this paper.

Note that hatching patterns and contouring sequencing do influence overall material properties of the build as well as the geometrical accuracy. Common practice is to hatch the layer first then finish the layer by laser contouring the edges of the geometry. The hatching of the next layer should be at least with a different angle from the previous one. Some machine suppliers are differentiating themselves by using their own patented angle rotations.

Ultimately, consistent powder composition and fixed machine parameters yield parts with repeating material properties that are on par, if not better in some areas, to those achieved from conventional casting of the same alloy composition. More detail is given in [1] on why PSM is confident in using the proprietary Nickel based super alloy and LPBF for gas turbine parts with revolutionary cooling technology designs.

EXTERNAL GEOMETRY PRECISION

Gas turbine airfoils exhibit a certain aerodynamic shape that is important to achieve in order to maintain engine performance. A slight deviation of a few degrees in incidence angle, or a change in flow cross-sectional area of the airfoil cascade (throat area) can easily impact turbine stage efficiency and power output. Hence the importance to achieve accurate geometry profiles of Nickel based super alloy turbine parts.

Conventional casting typically requires an iterative development process. Hard tooling is often adjusted in order to closely meet design intent geometry.

For additive manufacturing, no tooling is required but hardware may still exhibit deviations from residual thermal stress distortions. Consequently, adjustments to the CAD geometry provided to the additive manufacturing machine are required to achieve design intent. One approach consists of building a first additively manufactured part by using the design intent geometry as the input file to the machine. Deviations between build and

design intent are measured, and half of the opposite deviation amplitude is then applied to the new CAD geometry. This process is repeated until it achieves the expected dimensional tolerances. Needless to say that this iterative process can be expensive.

Significant development has been made on welding simulation tools, which have been effectively incorporated into additive manufacturing simulations. They start by de-featuring the build geometry to larger cubicle elements called “voxel” (analogy to volume and pixel) for which each voxel is used to solve the transient heat transfer situation of the welding process. The simulation then provides a relatively accurate prediction of local stresses and strains. The software can also be used to modify the CAD geometry accordingly in order to compensate for the predicted deflections. First time yield and development time can be significantly reduced by adopting this type of analyses.

Figure 4, shows the prediction of such a simulation tool for the deviation of a typical gas turbine airfoil. In this case, the largest geometrical deviation predictions showed up in the trailing edge area of the airfoil. This was expected since this area consists of several surface curvatures combined with an over-hang geometry shape situation. The second largest deviation prediction was less expected, and showed up on the pressure and suction side walls of the airfoil. This was potentially driven by several combined surface curvatures as well. Areas with less combined surface curvatures (or more prismatic sections) such as at the leading edge of the airfoil, showed very little deviations.

The orientation of a surface’s curvature relative to the build direction can have a strong impact on the build’s accuracy. One can optimize the orientation of a part within the build volume in order to minimize deviations. However, a different orientations may require the usage of support structure for the build. Areas with such attached support structures would require additional effort for removal and cleaning (blending) after the build. This can impact cost and finished surface precision.

So, in this airfoil application, PSM engineers oriented the parts specifically to avoid any need of support structure for the build, thus maximizing airfoil geometry accuracy and minimizing post processing manufacturing cost. This selected build orientation also allowed for the maximum number of airfoils (with a common orientation) to be built at the same time in the machine. This allows for further reductions of the piecewise

manufacturing cost. Note that accuracy of the internal cooling features, as described in the next chapter, were also a consideration when determining build orientation.

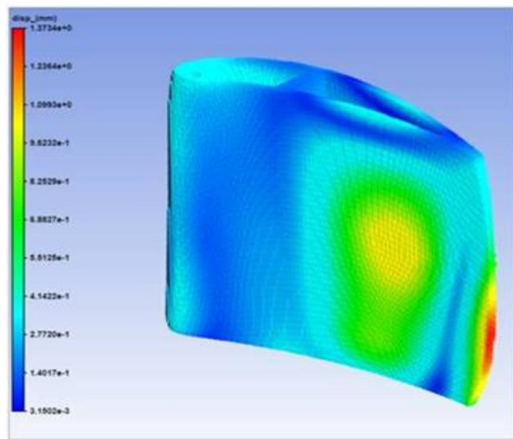


Figure 4: 3D scan prediction of airfoil shape additive manufactured with Nickel based super alloy, compared to original CAD file.

Although multiple airfoils were built (at the same time) at different locations on the build plate, they all yielded similar geometrical deviations relative to the CAD model used. This confirmed that build accuracy was largely driven by geometrical surface curvature and orientation relative to the build direction, as opposed to its position on the build plate.

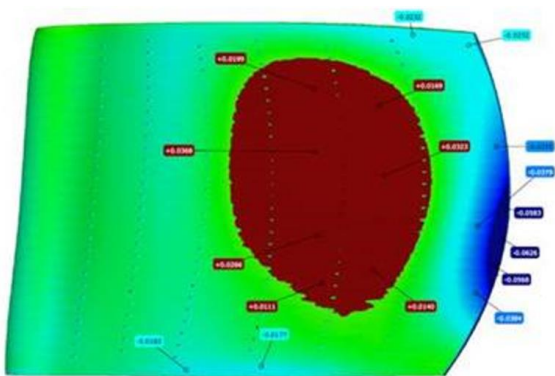


Figure 5: 3D scan results of airfoil shape additive manufactured with Nickel based super alloy, compared to original CAD file.

Figure 5 shows the actual external geometrical deviations of a LPBF manufactured part. Not only were deviations much smaller than those typically achieved through a conventional investment

casting process, they also closely matched the simulation predictions.

The impact of these small deviations on cross-sectional flow area change (throat area) was deemed acceptable with no impact on engine performance. The latter was further confirmed when parts were installed in the engine.

INTERNAL GEOMETRY PRECISION

Repeatable material properties and precise external geometries are critical but not sufficient for parts to operate successfully in a modern industrial gas turbine. Efficient cooling, accomplished through internal geometries, is necessary in order to sustain their integrity in a high gas temperature environment.

This is achieved by designing turbine airfoils with dedicated internal cooling features, through which cooling air can flow. For conventionally cast Nickel super alloy parts, it is common practice to introduce turbulators and pin fins along internal surfaces of the airfoil. Rows of cooling holes are also machined post casting, via EDM or laser drilling. With additive manufacturing, cooling features can be directly achieved by the build without the need for further machining. They can also have unique geometry shapes that were not possible to achieve through conventional manufacturing processes. There are however limitations in terms of internal cooling feature sizes and accuracies. For example, support structures of internal cooling features should be avoided since it is very unlikely to be able to remove them once the build is completed. Similar considerations need to be applied to powder removal in order to avoid having powder trapped in internal cooling cavities.

It is worth mentioning that the amount of cooling air used by the part is directly related to the cooling feature itself, from where it starts to where it ends. Flow is only passing through where sufficient cooling air pressure ratios exist. Consequently, if internal cooling feature sizes are inaccurate, or if surfaces exhibit higher roughness than expected, it is very unlikely to have a robustly cooled turbine airfoil.

To achieve successful turbine parts, PSM engineers brainstormed multiple cooling design ideas with the additive manufacturing capabilities and limitations in mind. One of the key cooling features developed was the so called PSM patented “radially tapered” cooling hole design as shown in Figure 6.

Such a cooling hole was designed to be placed as near as possible to the airfoil wall that requires

cooling. It was also designed to balance heat pick-up of the cooling and the film cooling effect of the neighboring holes. The goal of the cooling design was to generate a homogeneous and low temperature structure which used the least amount of cooling air.

In addition to the valuable cooling benefits, the shape of the “radially tapered” hole can accurately be achieved through LPBF. This is due to the down-skin surface areas only representing a small percentage of the overall hole surface (deviations from nominal shown in Figure 6). Also, such holes do not need any support structure during build up and do not pose any problem of powder removal post build. This makes them very suitable for additively manufactured Nickel based super alloy cooled turbine airfoils.

Note that this type of cooling hole is relatively insensitive to any external geometry deviations mentioned in the previous chapter, as it follows automatically the wall contour during the build.

Nonetheless slight differences between design intent and achieved build geometries may still exist, but these can be compensated by a simple scaling of the cooling feature as shown in Figure 7. The solid black curve is the geometry used in the CAD model by the machine, the solid green curve is the design intent cooling hole geometry. The remaining 3 lines are the scan results for each hole from the coupon build. One can see that the most critical portion of the hole, i.e. the flow controlling area at the exit, matches the design intent very well.

However, exit hole area is not the only element controlling the actual flow level. The other important feature is the overall hole surface roughness. The roughness achieved by LPBF is significantly different compared to conventionally machined holes.

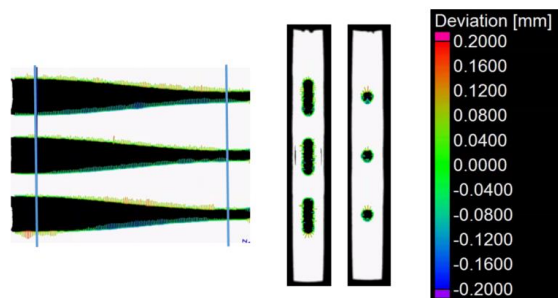


Figure 6: CT scan results of cooling hole shape additive manufactured with Nickel based super alloy, compared to original CAD file.

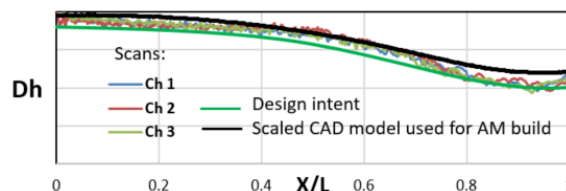


Figure 7: Hydraulic diameter evolution of the radially tapered hole. Comparison between actual part scans, design intent and scaled CAD model input for the build.

Figure 8 shows microscopic views of surface roughness variations observed around a LPBF hole. Figure 9 shows a more detailed microscopic view of the typically worst surface associated with this process, the down-skin.

Note that PSM uses a proprietary process to slightly alter these surfaces post additive manufacturing build. Nonetheless, significant surface roughness effects exist and need to be accounted for during cooling design development.

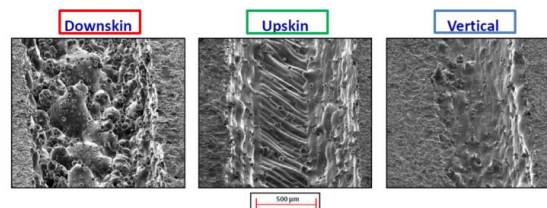


Figure 8: Microscopic views of cooling hole surface roughness as build from additive manufacturing with Nickel based super alloy.

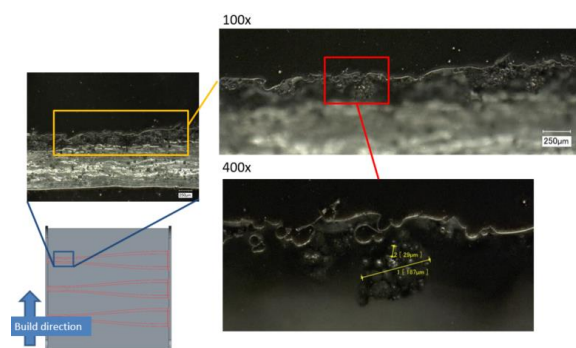


Figure 9: Microscopic views of the downskin surface of cooling holes additive manufactured with Nickel based super alloy.

In that regard, PSM collaborated with Penn State University (PSU) [2] to accurately quantify the roughness effects of LPBF cooling holes made

out of the PSM proprietary Nickel based super alloy. Several hole geometries and sizes were tested to quantify pressure losses and heat transfer coefficients for different operating pressure ratios [3]. The radially tapered cooling holes were confirmed to be the least impacted by the surface roughness across a large range of pressure ratios. This was due to the down-skin surface (the surface with the most predominant roughness) representing a much smaller fraction of the total surface area compared to straight cylindrical holes. Note that these test coupons were made using the PSM proprietary post process in order to improve surface finish. Ultimately the PSU coupon results enabled PSM to size and scale the radially tapered cooling holes in order to account for the deviations caused by the LPBF process.

The cooling hole scale factor was applied to the design of actual turbine airfoils manufactured by LPBF. When these larger scale components were evaluated by flow testing, the results confirmed the scale factor used. Figure 10 shows the results of the total flow test (black dots) and the design intent flow levels (solid line).

It is worth noting that the flow results also showed much higher consistency compared to those achieved by conventional manufacturing (+/- 4%).

The fact that additive manufacturing yields a smaller variability than conventional manufacturing methods is a great indication of a highly accurate and repeatable process. Therefore, LPBF is suitable for producing Nickel based turbine parts with accurate internal cooling features.

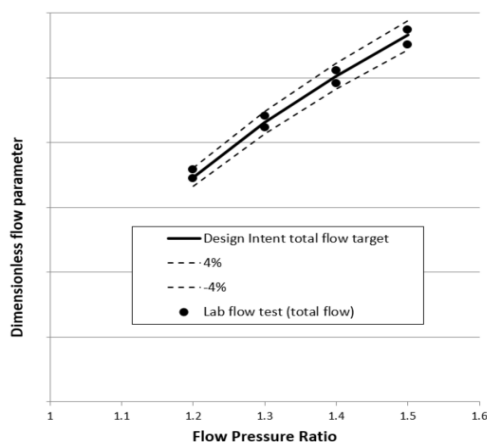


Figure 10: Lab flow test results and comparison with design intent flow level of cooled turbine airfoil additive manufactured with Nickel based super alloy.

CONCLUSION

In order to successfully produce hardware for gas turbine applications, precision manufacturing methods are required. LPBF provides an opportunity to do so, however careful attention has to be paid to a large number of factors which are:

- Powder chemistry and composition
- Laser energy density
- Hatching strategies
- Component build orientation and surface curvature
- Heat input and thermal stress
- Build distortion
- Surface roughness variation

In this paper, a series of development activities and process control methods associated with LPBF were described. These methods which yielded a robust and accurate process included:

- Selection of appropriate powder
- Machine core parameter and feature resolution optimization through DOE
- Build orientation evaluation
- Geometry distortion compensation through simulation
- Cooling feature scaling resulting from roughness effect evaluation

The combination of these elements resulted in a process which has been demonstrated to be appropriate for the manufacturing of precise nickel based turbine hardware.

There is a clear opportunity to apply this manufacturing technology to a larger production scale, which will in turn facilitate the incorporation of highly advanced designs into gas turbines.

REFERENCES

- [1] Day W., Kawecki E., McNally J., Rosenbarger T. Development and Material Characterization of a Selective Laser Melted Nickel Alloy for Turbine Applications. ASME turbo Expo GT2018-76614.
- [2] Snyder J.C., Stimpson C.K., Thole K. A., Mongillo D. Build direction Effects on Additively Manufactured Channels. ASME Transactions, Journal of Turbomachinery. May 2016, Volume 138, Issue 5.
- [3] Stimpson C.K., Snyder J. C., Thole K. A. Roughness effects on flow and heat transfer for additively manufactured channels. ASME turbo Expo GT2015-43940.

DESIGN AND EVALUATION OF A 3D PRINTED FLEXURE FOR A FAST STEERING MIRROR

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ABSTRACT

This paper presents the simulation and verification of a metallic and a 3D printed flexure for a fast steering mirror. Easy tuning can be important, because by adapting the stiffness of the flexure and thus the resonance frequency of the system to the scanning application the energy consumption can be reduced. Since the required resonance frequencies change with the application, a flexible manufacturing process, like 3D printing is required. The experimental results show that the measurements of the aluminium flexure match with the simulation. Due to the printing process major deviations between measurement and simulation are observable for the printed flexure, such that a geometrical variation is performed to analyze the influence of the characteristic dimensions on the stiffness of the flexure. Measurement results show that with the arm width the stiffness can be well tuned. It is shown that the power dissipation can be reduced by a factor of 6.8, if the stiffness is adapted to the scanning application.

1. INTRODUCTION

Fast steering mirrors (FSMs) are used in various technical applications, such as scanning optical systems [1], material processing [2] and tracking of objects [3]. Typically FSMs are electromagnetically [4] or piezoelectrically [5] actuated to achieve either a large scan range or high bandwidth, respectively. Their structure can be divided into a static and a moving part. The two parts are typically connected via a flexure, which stabilizes the mover around the pivot point and restricts motion in the non-actuated degrees of freedom [6]. Tuning the suspension mode to a desired frequency in the design phase can be important for the closed-loop control performance and system efficiency. By matching the frequencies with the drive frequencies of the targeted reference scan trajectory, the energy efficiency can be improved [7]. The suspension mode of the actuator is determined by the inertia of the mover and the stiffness of the system, which depends on the character-

istic dimensions of the flexure [6]. Flexures are most commonly made out of metal sheets, which are stamped or laser cut, such that an adaptation requires a significant manufacturing effort [8].

3D printing is already a well-established method for rapid prototyping [9] and is of increased importance for the production of final goods [10]. Due to a simple adaptation of printed parts to specific applications, they are already widely used in e.g. medical applications [11]. The most popular 3D printing technique is fused deposition modelling (FDM), which uses plastic filament as the raw material [12]. The plastic is available with a variety of mechanical properties, which ranges from a very stiff carbon fibre reinforced plastic to a rubbery thermoplastic polyurethane (TPU) [12].

The contribution of this paper is the design and evaluation of a 3D printed flexure. Section 2 describes the setup of the used FSM. In Section 3 the design and simulation results of an aluminium and a TPU flexure are presented. The dynamics of both system configurations are measured, analyzed and compared to the results of the simulation in Section 4. The influence of the characteristic dimensions of the flexure on the stiffness are further analyzed in Section 5. Section 6 concludes the paper.

2. FSM SYSTEM

A hybrid reluctance actuated FSM, with an actuation range of $\pm 3^\circ$, is used as a benchmark system. The main components of this actuators are a ferromagnetic core and mover, coils, suspensions and a magnet, which is used to create a DC biasing flux. Thru the coils this flux can be increased/decreased in the first/second air gap between mover and core, which yields to a torque on the mover (further described in [7]). The actuation principle itself is inherently unstable due to the negative stiffness introduced by the reluctance forces, such that a flexure, with a stiffness k of 47 mNm/deg, is required to stabilize the mover

around the pivot point. Since the actuator has a rotational inertia J of 6717 gmm², the resonance frequency f_r can be calculated with

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k}{J}} \quad (1)$$

to 100.7 Hz.

3. SIMULATION

Using finite element analysis (FEA) simulations, structural modes and frequency responses of mechanical structures can be determined up front, such that the flexure design can be easily adapted to the specific application. For the simulations, which are performed in ANSYS Mechanical (Ansys, Canonsburg, USA), the material properties need to be set in advance. The metallic flexure is made from aluminium (AW-1050A), with an elastic modulus of 69 GPa and a Poisson ratio of 0.3325, while the printed flexure is made out of TPU (Type: Ninjaflex, Ninjatek, Mannheim, USA), which has a stated elastic modulus of 12 MPa and a Poisson ratio of 0.4. Both flexures are used to stabilize the moving part of the hybrid reluctance actuated FSM around the pivot point. For the metallic flexure the resonance frequencies of both scan axes are set to 100 Hz, since the flexure is not designed for a specific scan application, while the printed flexure is designed for two different resonance frequencies for investigation purposes and since the drive frequencies of scan trajectories are typically unequal [13]. To compare the results of the two flexures the resonance frequencies of the printed flexure are set to 100 Hz and 130 Hz. The designs and suspension modes of both flexures, which are calculated using modal analysis, are shown in Fig. 1.

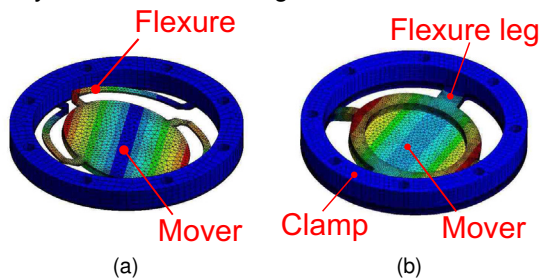


FIGURE 1. Results of the modal analysis. Suspension mode of (a) the aluminium flexure and (b) the 3D printed TPU flexure.

To analyze the system behaviour a harmonic analysis is performed. The results with both flexures are shown in Fig. 2. As can be observed,

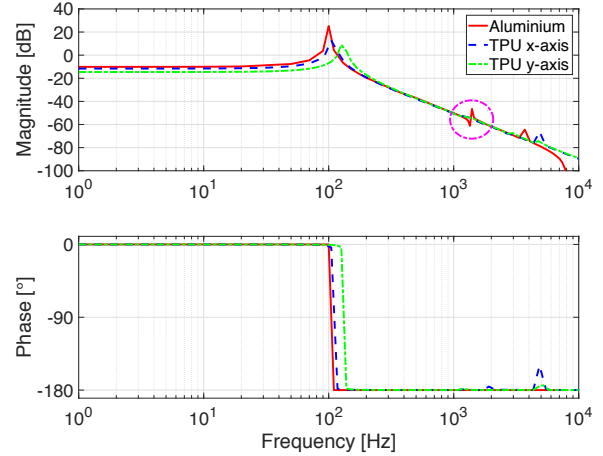


FIGURE 2. Simulated frequency response of the aluminium flexure (red) and the x- (blue) and y-axis (green) of the TPU flexure.

the resonance frequencies match the requirements. Due to the higher damping coefficient of the TPU flexure, the magnitude at the resonance frequency is slightly lower compared to the aluminium flexure. In the frequency response of the aluminium flexure (red solid) a structural mode at 1.4 kHz is observable (magenta circle). For feedback control, such modes be critical, as they can limit the achievable bandwidth [6]. The structural modes of the TPU flexure (blue, green) occur beyond 4 kHz, suggesting that higher control bandwidths may be feasible.

4. EXPERIMENTAL RESULTS

To validate the results of the simulation the system dynamics of both system configurations are measured with a system analyzer (Type: 3562A, Hewlett-Packard, Palo Alto, USA). In Fig. 3 the measured and simulated frequency response of the aluminium flexure is depicted. The measured magnitude response shows good agreement with the simulation in the frequency range of interest up to 1.5 kHz. The frequencies of the suspension mode (100 Hz and 109.6 Hz) and the first structural mode (1.4 kHz and 1.38 kHz) are almost equal for both system axes. In the phase response some deviations are notable, such as the additional phase lag in the measurement caused by the sensor dynamics, sampling delay and eddy currents of the actuator [4]. The measured phase strongly differs above 1.5 kHz, due to the system noise.

The TPU flexure is printed on a 3D printer (Type: Prusa i3 MK3, Prusa, Prague, Czech Republic), which uses the fused deposition modelling

method. In Fig. 4 the measurement results of the TPU flexure are compared to the simulation results.

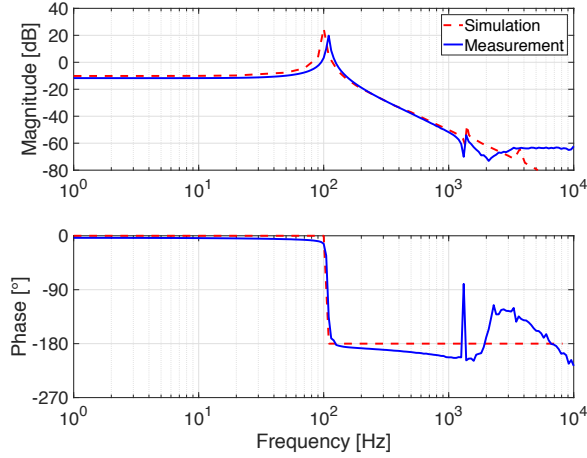


FIGURE 3. Measured and simulated frequency response of the system with the aluminium flexure.

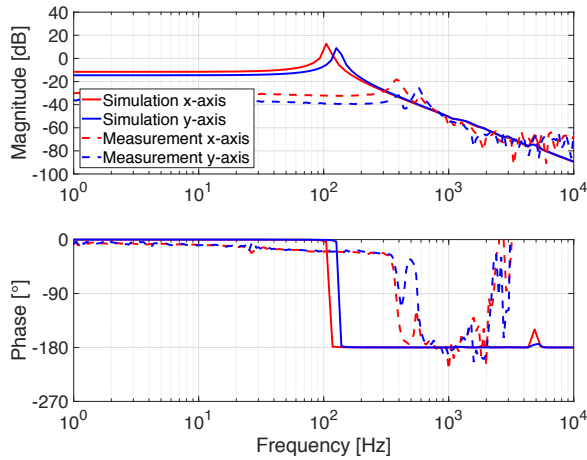


FIGURE 4. Measured and simulated frequency response of the system with the printed TPU flexure.

There are significant deviations observable, which are most likely caused by a change of the mechanical properties of the material during the printing process. The resonance frequencies of the two axes are at 380 Hz and 575 Hz, such that a deviation by a factor of 3.8 - 4 from the designed value can be calculate. Due to the noise floor the measurement is only valid until about 1.5 kHz, such that the structural modes are not observable. The mechanical properties of the material after printing could be determined with a mechanical test bench, such that an accurate simulation model can be generated. However, the elastic modulus and the Poisson ratio strongly depend on various parameters, like the used printer, the

printing temperature, the orientation of the part on the printer, etc. [14], such that determined parameter would only be valid for this specific flexure. In order to be able to apply the gained insights to a larger number of 3D printed flexures, the influence of the characteristic dimensions of the flexure on the stiffness are further analyzed.

5. GEOMETRICAL VARIATION

The characteristic dimensions of the printed flexure are the thickness t , the arm widths w_1 and w_2 , and the arm length l , which are depicted in Fig. 5.

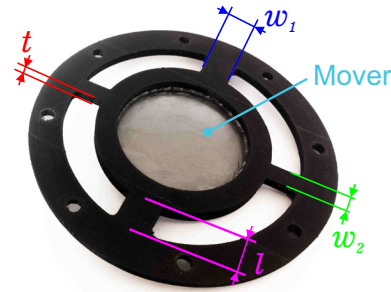


FIGURE 5. Characteristic dimensions of the printed TPU flexure.

The influence of the arm length l can only be analyzed properly, if the outer clamping dimension is also changed. However, due to the mechanical setup of the used FSM, extensive changes would be necessary to manipulate this parameter, such that the arm length is kept constant at 11 mm.

In Fig. 6 the measurement results of printed flexures of various thickness (2 mm - 4 mm) are shown. As can be observed, the frequency of the suspension mode is hardly affected by the flexure thickness (between 340 Hz and 380 Hz). The resonance frequency of the 2 mm flexure is, due to a slight pretension, even higher than the one of the 3 mm flexure. The reason for the low influence of the thickness on the stiffness of the flexure is most likely the high flexibility of the material and the large ratio between arm length (11 mm) and deflection (0.2 mm).

The measurement results for different arm width's are depicted in Fig. 7. As can be observed, by bisecting the width the frequency of the suspension mode is shifted for the tip axis from 367 Hz to 320 Hz and for the tilt axis from 582 Hz to 500 Hz. The resonance frequencies (black dots) are determined out of the measured frequency responses by considering the phase delay of the

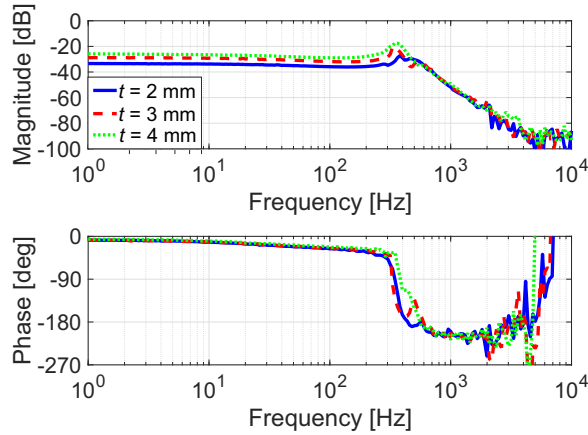


FIGURE 6. Measured frequency response for various TPU flexure thickness.

system, which can be divided into a constant phase shift of 5.5° , a time delay of $500 \mu\text{s}$, and the phase shift due to the mechanical resonance of 90° . The resulting reductions of the resonance frequencies are almost equal (12.8 % and 14 %), showing that with the arm width the stiffness of the flexure can be well tuned.

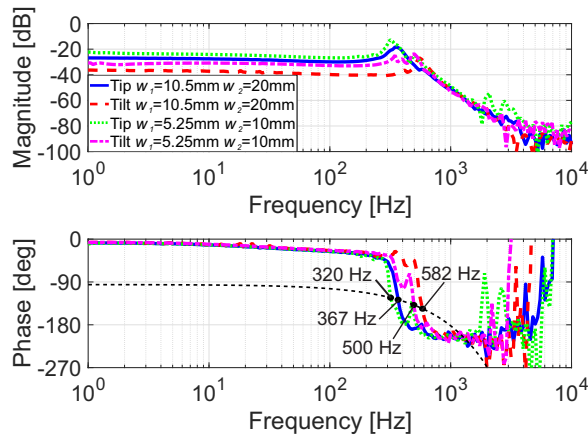


FIGURE 7. Measured frequency response for different flexure arm widths.

To analyze the improvement of the energy efficiency, due to the tuned resonance frequencies, the power dissipation of the actuator is measured at a constant scan amplitude of 0.2° for different flexures. The power dissipation is determined with the measured terminal voltage of the amplifier and the current through the coils (see [4]). Initially the flexure with the following dimensions $w_1=10.5 \text{ mm}$ and $w_2=20 \text{ mm}$ is used. At a driving frequency of the sinusoidal signal of 320 Hz for the tip axis, a power dissipation of 27.3 W is measured. The applied frequency matches the

resonance frequency of the tip axis of the flexure with the bisected arm width (see Fig. 7). If the same driving signal is applied to the tip axis of this flexure ($w_1=5.25 \text{ mm}$ and $w_2=10 \text{ mm}$), the power dissipation decreases to 4 W. By matching the resonance frequency with the driving frequency, the power consumption can be reduced by a factor of 6.8 for the shown case.

In summary a 3D printed flexure with different resonance frequencies is designed and the influence of the characteristic dimensions on the resonance frequency is shown, revealing that the resonance frequency can be adapted to the scan application and the power consumption can be reduced by a factor of 6.8 by matching the driving frequency with the resonance frequency.

6. CONCLUSION AND FUTURE WORK

In this work a metallic and a 3D printed flexure for a FSM are designed and tested. The results of an FEM simulation are compared to the measured dynamics. The measurement results of the aluminium flexure show good agreement with the simulation, verifying the design. For the printed flexure significant deviations between simulated and measured stiffness are observable, caused by the deviation of the mechanical properties, due to the printing process. Further analysis of the influence of the characteristic dimensions on the stiffness of the flexure shows that the stiffness can be well tuned by adjusting the arm width of the flexure. Tuning the systems resonance frequency to the desired drive frequency, the power dissipation can be reduced by a factor of 6.8. Future work includes the determination of the printed material properties to enable a better prediction of the stiffness and mechanical properties of 3D printed flexures.

ACKNOWLEDGMENTS

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REFERENCES

- [1] Schlarp J, Csencsics E, Schitter G. Optical scanning of laser line sensors for 3D imaging. *Applied Optics*. 2018;57(18):5242–5248.

- [2] Hedding LR. Fast steering mirror design and performance for stabilization and single axis scanning. In: Acquisition, Tracking, and Pointing IV. vol. 1304. International Society for Optics and Photonics; 1990. p. 14.
- [3] Mokbel HF, Yuan W, Ying LQ, Hua CG, Roshdy AA. Research on the Mechanical Design of Two-Axis Fast Steering Mirror for Optical Beam Guidance. Proceedings of 2012 International Conference on Mechanical Engineering and Material Science (MEMS 2012). 2012;.
- [4] Csencsics E, Schlarp J, Schitter G. High performance hybrid-reluctance-force-based tip/tilt system: Design, control and evaluation. IEEE Transactions on Mechatronics. 2018;Accepted.
- [5] Park JH, Lee HS, Lee JH, Yun SN, Ham YB, Yun DW. Design of a piezoelectric-driven tilt mirror for a fast laser scanner. Japanese Journal of Applied Physics. 2012;51(9S2):09MD14.
- [6] Munnig Schmidt R, Schitter G, Rankers A, van Eijk J. The Design of High Performance Mechatronics. 2nd ed. Delft: IOS Press; 2014.
- [7] Csencsics E, Schitter G. System Design and Control of a Resonant Fast Steering Mirror for Lissajous-based Scanning. IEEE Transactions on Mechatronics. 2017;22(5):1963–1972.
- [8] Lobontiu N. Compliant mechanisms: design of flexure hinges. CRC press; 2002.
- [9] Mellor S, Hao L, Zhang D. Additive manufacturing: A framework for implementation. International Journal of Production Economics. 2014;149:194–201.
- [10] Effenberger I. Multisensorische Inspektion von additiv gefertigten Kunststoffbauteilen. Multisensorik in der Fertigungsmesstechnik 2018. 2018;p. 169–172.
- [11] Gibson I, Rosen D, Stucker B. Additive Manufacturing Technologies. New York: Springer; 2014.
- [12] Ning F, Cong W, Qiu J, Wei J, Wang S. Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling. Composites Part B: Engineering. 2015;80:369–378.
- [13] Tuma T, Lygeros J, Kartik V, Sebastian A, Pantazi A. High-speed multiresolution scanning probe microscopy based on Lissajous scan trajectories. Nanotechnology. 2012;23(18):185501.
- [14] Tymrak B, Kreiger M, Pearce JM. Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. Materials & Design. 2014;58:242–246.

INTERNAL SURFACE TOPOGRAPHY AND DIMENSIONAL METROLOGY OF MICROWAVE GUIDE USING X-RAY CT

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INTRODUCTION

Additive manufacturing (AM) offers several benefits, including parts consolidation and lightweighting, and can be particularly attractive in applications where the desired geometry cannot be made another way. An example is the satellite microwave guide that has been put forward by Renishaw [1]. The internal surface topography and dimensional accuracy of the internal channel are critical to efficient microwave transmission. However, internal features are difficult to characterize non-destructively. Therefore, measurement of surface topography and dimensional accuracy using X-ray microscale computed tomography (μ CT) is of interest for the internal channel.

There is a growing body of work seeking to understand the use of μ CT for dimensional measurement in AM [2], and for surface topography in AM [3]. μ CT accommodates geometrical complexity both internal and external to additively manufactured parts. The purpose of this paper is to report the results obtained to date in an ongoing collaborative project to establish reliable characterization methods for surface topography and dimensional accuracy using μ CT. Hatch rotation angle became of interest after it was observed that periodic roughness features appeared to align with what would be expected for the 67° hatch rotation used.

METHODS

A standard WR34 cross section was used to print the microwave guide having geometry shown in *FIGURE 1*. The material is Ti6Al4V and printing was performed on a Renishaw AM400 additive manufacturing system. The waveguide external surface was lightly shot-peened after removing the support material. Six additional Ti6Al4V samples were printed, each having a length of 10 mm and the WR34 cross section with no post-treatment of any surface. These six short samples differed by the hatch

rotation angle per layer and were printed to have the standard WR34 cross section.



FIGURE 1. (left) Approximate position of the region of interest on the complete waveguide. (right) Geometry and build orientation of the short waveguide sections.

Hatch rotation angle is an adjustable process parameter in metal powder bed fusion AM techniques, specifying the layer-by-layer rotation of the melt track orientation. Hatch rotation angle impacts the frequency at which the bulk hatching meets a given sidewall, as well as the layer frequency at which hatch orientation is repeated.

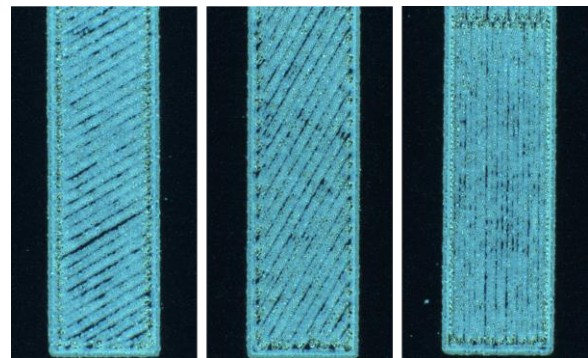


FIGURE 2. Example of counter clockwise hatch rotation angle per layer of 30 degrees.

All hatch rotations are counter clockwise per layer and use a 10mm stripe strategy. An example of a 30° rotation is shown in *FIGURE 2*,

which were obtained by printing a single layer on an anodized aluminum plate.

Imaging of the additively manufactured samples was conducted using an Xradia Versa 520 μ CT system (Zeiss, USA) with a 120 kV source potential, LE6 filter (proprietary, Zeiss), and 1001 projections over 180 degrees. The smaller waveguide sections were scanned with 2.2 s exposure (120 mm source to detector spacing) while the same field of view on the larger, full waveguide sample required 4.5 s exposure due to the added distance between source and detector (180 mm source to detector spacing). This resulted in scan times ranging from 90 to 120 minutes. A 0.4x optical magnification was combined with 4.4x geometrical magnification, resulting in a voxel size of 7.8 μ m in all scans, with exception to the high-resolution scan performed, which used 4.0x optical magnification and 2.2x geometrical magnification resulting in a voxel size of 3.0 μ m. For ease of scanning and image processing, custom sample holders were manufactured in ABS plastic to fix the samples into a repeatable orientation.

Tomography data was reconstructed using the Zeiss Reconstruction software package, with uniform byte scaling across scans. After reconstruction, no noise-reducing filtering was required, and a single threshold value was manually chosen to identify the external boundary of the part. The resulting binary 3D images were analyzed using custom algorithms written using Matlab.

A laser confocal microscope (Keyence VK-X210) was used on external surfaces of the full waveguide sample. The objective lens was 10X with Z pitch of 2 μ m and X, Y resolution of 2.79 μ m. Raw height maps were exported from the Keyence proprietary software for processing in Matlab.

Measurements of internal channel geometry were performed on all six short samples using a Wenzel LHG 12.16.10 CMM equipped with a Renishaw Revo-2 continuous 5-axis measuring head and 1.5 mm diameter probe. The CMM point cloud data was imported into Geomagic Control X software for measurement. Point clouds were constructed in Matlab from each of the six 3D binary μ CT images and exported to Geomagic Control X software for measurement.

SURFACE TEXTURE

To assess the capability of μ CT for qualitative comparison of surface texture among the different samples, two sets of comparisons were conducted over the same evaluation area. The first measurement was conducted on an as-printed downskin surface of the 180° hatch rotation sample. The second was conducted on a lightly shot-peened downskin surface of the full waveguide. Both measurements were performed on surface C in FIGURE 3.

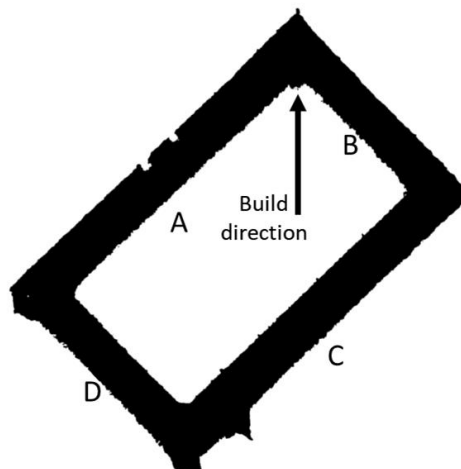


FIGURE 3. Cross section of one WR34 sample identifying downskin surfaces A, B, C, and D.

As-printed Surface

Three sets of measurements were performed on a 2.5mm x 2.5mm patch on surface C (see FIGURE 3) of the 180° hatch rotation sample. Data from the laser confocal microscope comprised one data set, while the other two data sets were obtained via μ CT at two different voxel resolutions. The high-resolution μ CT voxel size was 3.0 μ m, which was chosen to more closely match the in-plane resolution of the laser confocal microscope of 2.8 μ m. The low-resolution μ CT voxel size was 7.8 μ m, which was chosen as the smallest voxel size that permits the full WR34 cross section to be contained in the reconstructed 3D image.

FIGURE 4 shows the surface height maps obtained from each measurement as well as the line used to extract profiles for comparison purposes among the methods. It is evident that the high-resolution μ CT data captures the smallest scale features of the three data sets.

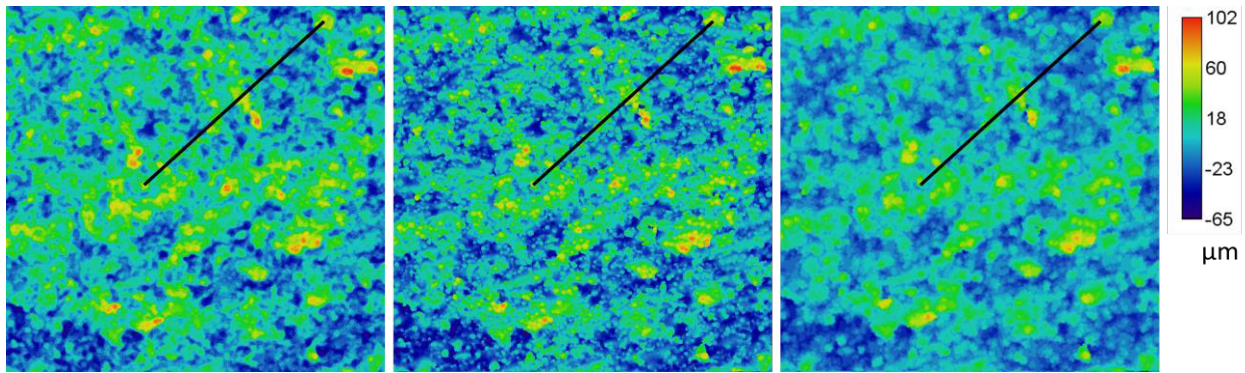


FIGURE 4. Height maps showing (left) laser confocal data, (middle) high-resolution μ CT ($3.0\ \mu\text{m}$ voxel) capturing partially melted particles on the surface, and (right) low-resolution μ CT ($7.8\ \mu\text{m}$ voxel). Black lines indicate the locations of the extracted profiles shown in FIGURE 5 and FIGURE 6.

FIGURE 5 shows surface height profiles extracted from the same evaluation area of the 180° sample after performing a Gaussian F-operation with $2.5\ \text{mm}$ cutoff length. No additional S or L filters were applied at this stage in order to allow comparison of the differences among each data set. The laser confocal data more closely follows the profile measured by the high-resolution μ CT, while the profile obtained by the low-resolution μ CT shows a comparably damped signal with reduced amplitude.

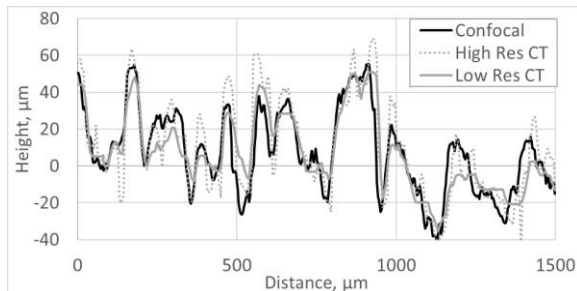


FIGURE 5. Profiles of leveled data, after performing a Gaussian F-operation with $2.5\ \text{mm}$ cutoff with each profile extracted from the same evaluation area on the 180° sample.

Three common field parameters for each measurement performed on the $2.5\ \text{mm} \times 2.5\ \text{mm}$ area are summarized in

TABLE 1, specifically the arithmetic mean roughness, S_a , root mean square roughness, S_q , and peak height, S_z . These values follow the expected trend as observed in FIGURE 5.

The goal is to determine a set of filters that allow comparison of internal surface texture among the six different samples having different hatch rotation angles. Each of these samples was scanned at the voxel resolution of $7.8\ \mu\text{m}$ to

allow for additional characterizations including measurement of the internal geometry of the channel as well as porosity.

TABLE 1. Comparison of areal field parameters evaluated on the as-printed surface (surface C) on the 180° sample. A Gaussian F-operation using a $2.5\ \text{mm}$ cutoff was performed to level the data. No S or L filters were performed at this stage.

Field Parameter	Laser Confocal Microscope	High Res. X-ray CT	Low Res. X-ray CT
$S_a, \mu\text{m}$	16.4	18.3	14.4
$S_q, \mu\text{m}$	20.5	22.8	18.2
$S_z, \mu\text{m}$	154	168	139

The coarsest height map belonged to the low-resolution μ CT case ($7.8\ \mu\text{m}$ voxels). Therefore, a Gaussian convolution S-filter with a $20\ \mu\text{m}$ cutoff wavelength was used, which results in a kernel size of 4 pixels. Of primary interest in the comparison among samples is the detection of tall roughness features that were observed on downskin surfaces during previous waveguide builds when using the 67° hatch rotation angle. TABLE 2 summarizes the S_a values for three different scale-limited surfaces. It is apparent that the low-resolution μ CT measurement is insufficient to capture the small-scale roughness features of as-printed surfaces. However, the waviness surface has better comparison to the other two measurements and was therefore used to qualitatively compare the data among each sample. The $125\ \mu\text{m}$ cutoff value was chosen based on visual inspection of the surface and the more comparable waviness field parameters summarized in TABLE 2.

TABLE 2. Comparison of S_a values, μm , for three surface types.

Surface Type	Laser Confocal	High Res. X-ray CT	Low Res. X-ray CT
Short Scale SF Surface*	15.1	15.6	13.1
Short Scale SL Surface**	9.3	10.1	7.3
Middle Scale SF Surface*** (Waviness)	9.9	9.8	9.1

* F-operator, $20\ \mu\text{m}$ S

** F-operator, $20\ \mu\text{m}$ S, $125\ \mu\text{m}$ L

*** F-operator, $125\ \mu\text{m}$ S

FIGURE 6 shows the resulting waviness profiles extracted from the same evaluation area as shown above in FIGURE 5. Comparability among the measured waviness field parameters for the laser confocal microscope and the two different μCT resolutions on surface C of the 180° sample is improved due to the bandwidth matching provided by the Gaussian convolution filters.

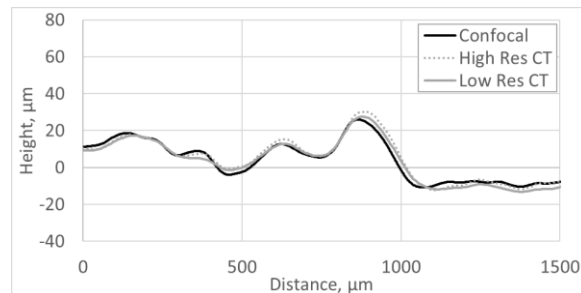


FIGURE 6. Waviness profiles (F-operation with 2.5mm cutoff, S-filter with $125\ \mu\text{m}$ cutoff), for the same profiles shown in FIGURE 5.

The values reported in TABLE 2 suggest that μCT can make reliable surface texture measurements, as suggested previously [4]. The same algorithm was used to perform the Gaussian convolution filters (implemented in Matlab with symmetric edge correction) for both the laser confocal data and the μCT data. Differences between the measured results are related to the nature of the measurement (laser vs X-ray) and the manual segmentation of the μCT images required to obtain the surface of interest. Cropping of the regions of interest from the measured data was also performed manually, without algorithmic registration of the two data sets beforehand. Work is ongoing to improve robustness of comparisons between the

laser confocal measurements and μCT measurements.

Shot-peened Surface

The complete printed waveguide underwent light shot peening after removal from the build plate. The effect of this surface post-processing is the removal of small-scale roughness features. Both the laser confocal microscope and the low-resolution μCT ($7.8\ \mu\text{m}$ voxel) were used to scan surface C after this surface treatment. FIGURE 7 shows profiles extracted from the evaluation area for both the laser confocal and μCT data. The data agree well, as summarized in TABLE 3. The removal of small-scale features inaccessible to the low-resolution μCT ($7.8\ \mu\text{m}$ voxel) by shot peening inherently improves the bandwidth matching between the two measurements methods, and thus the comparability of the reported field parameters.

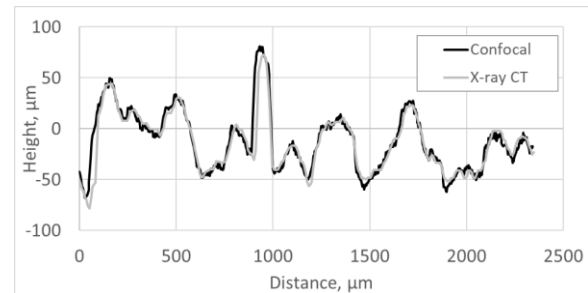


FIGURE 7. Profiles extracted from a $2.5\ \text{mm} \times 2.5\ \text{mm}$ area for both the laser confocal microscope and low-resolution μCT ($7.8\ \mu\text{m}$ voxel). Only an F-operation with $2.5\ \text{mm}$ cutoff was used.

TABLE 3. Field parameters from the short-scale SF surface (F-operation with $2.5\ \text{mm}$ cutoff and S-filter with $20\ \mu\text{m}$ cutoff).

Field Parameter	Laser Confocal Microscope	X-ray CT ($7.8\ \mu\text{m}$ voxel)
$S_a, \mu\text{m}$	21.2	21.5
$S_q, \mu\text{m}$	26.4	26.7
S_{sk}	0.34	0.20
S_{ku}	2.98	2.84
$S_z, \mu\text{m}$	174	172

Effect of Hatch Rotation Angle

The hatch rotation per layer was rotated counter clockwise through different angles for each of the six samples. These angles are 0° , 30° , 45° , 67° , 90° , and 180° . The waviness height map is shown for each of the six samples in FIGURE 8,

while the corresponding field parameters are summarized in TABLE 4.

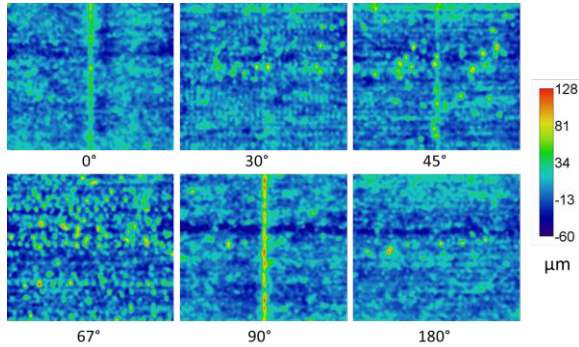


FIGURE 8. Waviness height maps using *F*-operation and *S*-filter with 125 μm cutoff.

Each sample uses a 10 mm stripe strategy for the hatch pattern. For the 0°, 45°, and 90° samples, a central ridge is evident where the two pattern segments meet. To provide a fair comparison of the waviness field parameters, four 2.5mm x 2.5mm patches were selected as shown in FIGURE 9, with the mean of these four patches being reported in TABLE 4.

TABLE 4. Waviness field parameters using *F*-operation with 2.5 mm cutoff, *S*-filter with 125 μm cutoff.

Hatch Rotation	S_a , μm	S_q , μm	S_z , μm
0°	10.2	12.8	84
30°	11.0	14.9	111
45°	13.3	18.6	143
67°	17.5	22.5	147
90°	13.2	17.0	118
180°	11.8	15.0	110

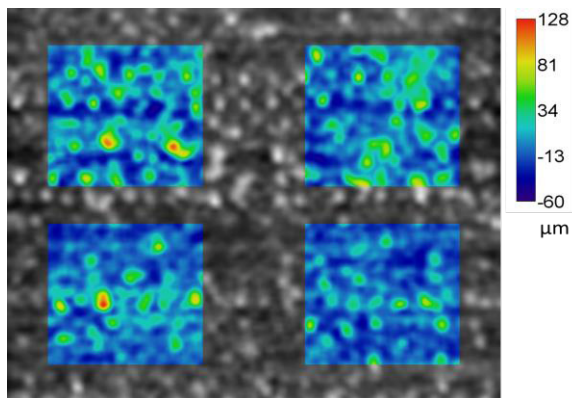


FIGURE 9. Demonstration of the four locations at which the waviness field parameters were measured. Reported values in TABLE 4 are the mean of these four areas.

DIMENSIONAL MEASUREMENT

The 3D binary images used for the surface texture measurements were also used for dimensional measurements of the internal channel and were compared to tactile CMM measurements. TABLE 5 summarizes the width and height of the internal channel as measured by the CMM.

TABLE 5. Summary of CMM measurements of the internal WR34 channel on each of the six short samples.

Hatch Rotation	Width [mm]	Height [mm]
CAD	4.318	8.636
0°	4.252	8.594
30°	4.247	8.580
45°	4.238	8.582
67°	4.206	8.531
90°	4.263	8.624
180°	4.310	8.597

A point cloud of the surfaces identified from the μCT data was generated using custom code written in Matlab. Unlike X-ray μCT measurement, the tactile CMM probe can only access the high points of the surface during measurement. Therefore, to improve comparability between the two measurement methods, a 3D morphological closing operation using a spherical structural element was performed on the μCT data to simulate the surface that is accessible to the 1.5mm diameter probe. FIGURE 10 illustrates the reconstructed waveguide and regions internally and externally accessible to the probe.

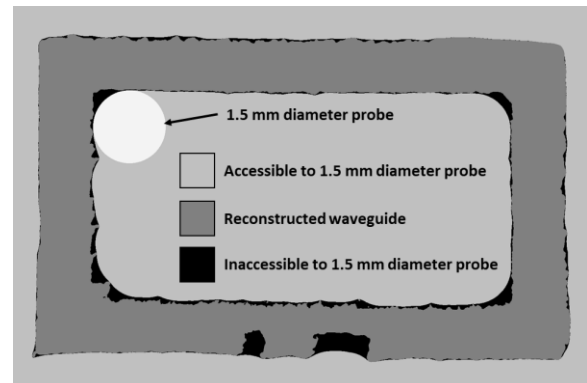


FIGURE 10. Cross section of waveguide (dark grey) showing the region accessible to the 1.5 mm diameter probe (light grey), and region inaccessible to the probe (black).

The μ CT calibration procedure for these dimensional measurements involved scanning a cylindrical, $6.350 \text{ mm} \pm 0.020 \text{ mm}$ diameter titanium rod at the same scan settings as were used to scan the waveguide samples. The calibrated voxel resolution was obtained by dividing the known rod diameter in μm by the measured rod diameter in voxels.

Table 6 summarizes dimensional measurements of the width and height of the internal channel that were made using μ CT (by simulating the surface that would be accessible to the tactile probe). The deviation between the CMM and μ CT measurements are also summarized in Table 6.

Table 6: Summary of μ CT measurements of the internal WR34 channel on each of the 6 short samples. The point cloud was generated by simulating the surface accessible to a 1.5 mm diameter probe tip for comparability to the CMM measurements.

Hatch Rotation	Width [mm] ± 0.031	Width Dev. [mm]	Height [mm] ± 0.048	Height Dev. [mm]
0°	4.284	0.032	8.618	0.024
30°	4.276	0.029	8.603	0.023
45°	4.269	0.031	8.605	0.023
67°	4.239	0.033	8.559	0.028
90°	4.294	0.031	8.639	0.015
180°	4.334	0.024	8.621	0.024

SUMMARY

Using the hatch rotation case study, it was determined that μ CT can provide highly useful comparative and even accurate measurements, limited by the scanning resolution. On as-printed surfaces, it was found that μ CT out-performed the laser confocal microscope at feature detection and roughness measurements when in-plane resolutions were matched between the techniques ($\sim 2.8 \mu\text{m}$). However, μ CT failed to provide accurate roughness measurements on the same surfaces when the voxel resolution was scaled to allow for CMM measurements ($7.8 \mu\text{m}$). The difficulty in capturing as-printed surfaces is explained by the presence of narrow features on the order of single fine particles. Light shot-peening of the surface was found to remove such features and allow even the lower resolution μ CT scan to accurately represent the surface.

Internal dimensional measurements were found to be consistently $15\text{-}33 \mu\text{m}$ larger when using μ CT with $7.8 \mu\text{m}$ voxels, compared to CMM results. This consistent deviation can be explained as losing the highest points of the roughness features (as discussed above) combined with any measurement error on either machine (e.g. voxel size determination).

In general, μ CT is shown to be a streamlined tool for capturing multiple measurements while conducting process parameter studies. The accuracy is limited to the feature resolution; however, a-priori knowledge of the surface characteristics can allow measurement resolutions to be adjusted accordingly. One major factor that was not discussed in this paper was the additional information of porosity and inclusions that is obtainable through μ CT. The combination of roughness, dimensional, and defect analysis (and any spatial correlations in between) provide a strong value proposition for including the μ CT into standard development practices.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] Saunders M. Meeting the Machining Challenges of Additive Manufacturing. Modern Machine Shop, 2017; Vol. 90, No. 5, 78-83.
- [2] Thompson A, Maskery I, Leach R K. X-ray Computed Tomography for Additive Manufacturing: A Review. Measurement Science and Technology. 2016; 27: 57-68.
- [3] Thompson A, et al. Measurement of the Internal Surface Texture of Additively Manufactured Parts by X-ray Computed Tomography. in: 7th Conference on Industrial Computed Tomography (iCT 2017), February 7-9.
- [4] Thompson A, et al. Internal Surface Measurement of Metal Powder Bed Fusion Parts. Additive Manufacturing. 20. 126-133

PRECISION ADDITIVE METAL MANUFACTURING

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INTRODUCTION

Additive Manufacturing (AM) is an increasingly used production method with the ability to evoke a revolution in manufacturing due to its almost unlimited design freedom and its capability to produce personalised parts locally and with efficient material use [1]. Currently still several technological challenges remain such as a limited precision due to shrinkage, build-in stresses and dross formation at overhanging structures (see Figure 1) and a limited process stability and robustness. Moreover post-processing is often needed as as-processed parts have a high surface roughness and might have, in some cases, remaining porosity.

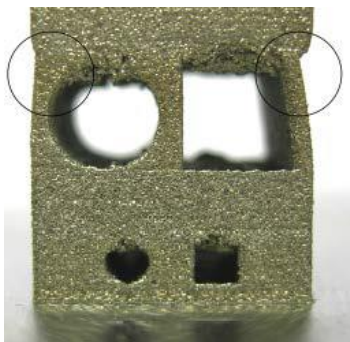


FIGURE 1. Deformation due to tensile stresses and dross formation in overhanging structures [2].

For AM to become fully accepted by endusers from different sectors, it must be developed into a true precision manufacturing method. The production of precision parts relies on three principles:

- (1) The production is robust, i.e. that all sensitive parameters can be controlled.

- (2) The production is predictable, e.g. the shrinkage or warpage that occurs is acceptable because it can be predicted and compensated in the design.

- (3) The parts are measurable, as without metrology accuracy, repeatability and quality assurance cannot be known.

Next to these principles ensuring robust & predictable production, we should also work on improving the overall quality of the produced part (density, roughness, precision, ...).

PAM², which stands for **Precision Additive Metal Manufacturing**, is a European MSCA project in which 10 beneficiaries and 2 partners collaborate on improving the precision of metal Additive Manufacturing [3]. Within this project, research is done for each process stage of AM, going from the design stage to modelling, fabricating, measuring and assessment. For each step we aim to progress the state of the art with a view on improving the final AM part precision and quality by implementing good precision engineering practice.

In this article we will list PAM²'s detailed objectives, the envisioned approach and the results achieved after 1,5 years of research.

OBJECTIVES

The overall objective of PAM² is to ensure the availability of **high precision AM processes and (computational) design procedures**. Detailed objectives to reach this overall goal are:

- (1) to develop **advanced (computational) design tools**, enabling competitive designs, better use of AM possibilities

against minimal design costs and reduced time-to-market

- (2) to develop better **modelling tools for first-time-right processing**
- (3) to **optimize selective laser melting process strategies** for improved part precision and feature accuracy
- (4) to understand the link between post-process metrology and in-process observations, creating the basis for **in-process quality control and process stability**
- (5) To develop **innovative in-process and post-process techniques** to reduce or remove roughness, porosity and internal stresses and to improve dimensional accuracy and mechanical properties.

APPROACH

The objectives listed above will be reached by progressing the scientific/technical knowledge beyond the state-of-the-art, through implementing good precision engineering practice, by cross-linking every step along the process chain and by providing feedback for each stage after technology and product assessment. The AM process steps, the interaction between the steps, the assessment feedback loop and the role of the end-users are shown in Figure 2.

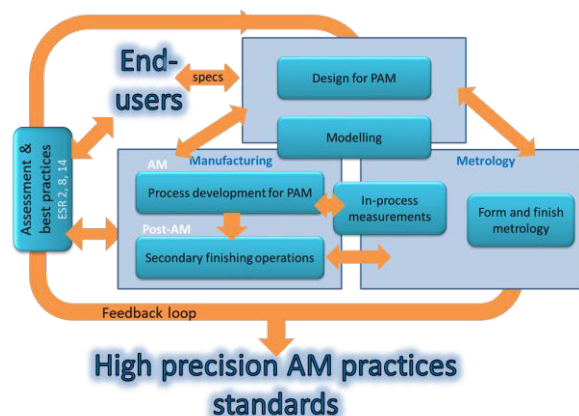


FIGURE 2. A schematic overview of the research done within PAM² for each step of the AM process chain and the interactions between these steps.

The specific metal AM processes that are investigated in this project are powder bed- and laser-based fusion (e.g. Selective Laser Melting or SLM) of maraging steel, TiAl6V4 and inconel 718.

RESULTS

Design

To fully exploit the advantages of AM's associated design freedom, topology optimization is often used to generate an optimal design for an AM part. Current topology optimization tools however do not take into account that local overheating during AM processing might occur. This overheating can result in microstructural inhomogenities, defect formation, poor surface finish and undesired deformation and/or mechanical properties for the final AM part. Within the design work package of PAM² a computationally inexpensive simplified thermal model, called a 'hotspot detector', is developed to detect zones of local heat concentration [4]. Finite element implementation of the hotspot detector can be integrated with the density based topology optimization in order to generate robust AM designs that are expected to be free of local overheating zones (Figure 3). An important advantage of this physics based method over already existing geometry based approaches is that it incorporates the temperature response of a geometry instead of imposing explicit prohibition of overhangs. The later is found to be occasionally overrestrictive, leading to sub optimal designs while in some cases it is insufficient for constraining local overheating.

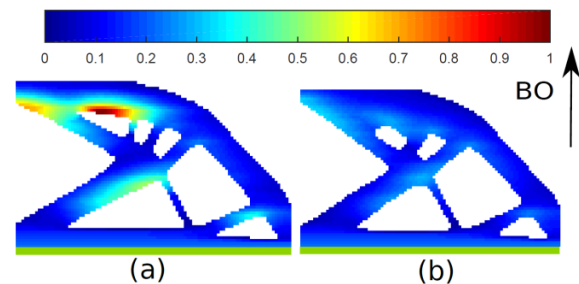


FIGURE 3. Normalized temperature fields superimposed on designs obtained by (a) Standard Topology Optimization (TO) (b) Hot spot constrained TO for minimum compliance against cantilever loading [4].

Modelling

Within PAM² modelling is done both for the AM process and the AM post-process. Full numerical modelling of an SLM process is normally very time-consuming [5]. Simulating even a single layer of a tiny part needs a lot of computation time. As a result, full numerical simulations cannot be extended to bigger parts. Because of this issue, a novel strategy has been developed within PAM² in order to enable one to do a full

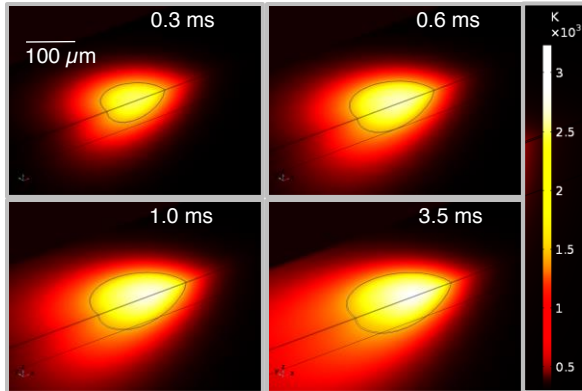


FIGURE 4. Temperature contour and melt pool shape at four different times [7]

thermo-mechanical simulation for an actual metal part made by SLM. The method is based on a combination of a full thermo-fluid dynamic model (including Marangoni effects) and a lumped model which reduces the required computation time, while keeping an acceptable accuracy (Figure 4). This way complete parts can be simulated and possible issues can be detected before processing, again ensuring that final AM parts have the quality and precision that is needed. The model can for example be used to predict porosity formation [6] and the morphology of the grains of a Ti6Al4V part produced by selective laser melting [7].

At the same time experimental trials are carried out to evaluate the effects of different SLM parameters on the obtainable part quality (see next paragraph). The results of these experiments would facilitate the modelling and subsequent optimization of the SLM process for producing highly precise components.

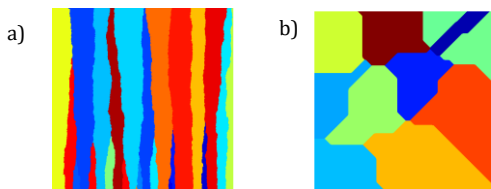


FIGURE 5. The initial (columnar) microstructure on the left (a) and the equiaxed microstructure after heat treatment on the right (b) [7].

Finally, cellular automata is used to model the microstructural evolution during post-processing. Figure 5 shows the result after a uniform heat treatment at the beta transus temperature. The model shows good agreement with earlier experimental results [7].

Processing

In order to evaluate different AM processes and machines and also to track the progress within PAM², a benchmarking design was made (Figure 6 and 7) [8]. This design will enable to evaluate accuracy and precision of the machine, residual stresses in the parts, homogeneity (in terms of density and residual porosity), build speed, mechanical properties, surface finish and corrosion resistance. It also includes features that represent a challenge for AM, which allows us to track the new developments on improving the precision of AM within PAM².

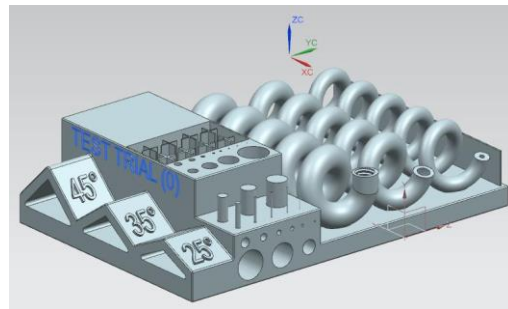


FIGURE 6. PAM² benchmark part [8].

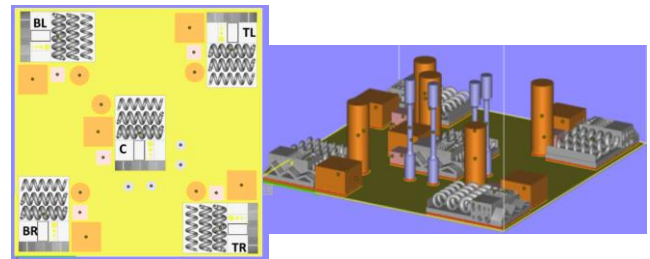


FIGURE 7. PAM² benchmark job [8].

One of these new processes that was developed within PAM² is the use of a dynamic focusing unit in order to combine high productivity for the inner AM part by using a large spot size (defocused beam) with high outer precision by using the smallest spot size (focused beam) [9].

The surface quality and dimensional accuracy of critical down-facing surfaces produced by SLM was investigated as well [10]. It was found that the presence of partially molten powder and dross formation is the major cause of surface defects within the down-facing surfaces of parts. Further results indicate that only looking at the roughness does not provide reliable information on the presence and formation of dross. Dimensional accuracy tests are also required and are the focus in [11].

Post-processing

AM parts might need post-processing as the final surface roughness is often higher than what is allowed for most applications. This roughness can be reduced by laser polishing. A small amount of material is first ablated and/or molten through laser irradiation, and subsequently redistributed to create a surface with a lower roughness and sometimes also new functionality. Laser polishing has a high process speed and the capability for localized surface treatment.

Within PAM² both in-process (by using a hybrid AM process) and post-process laser polishing is investigated. For the post-process laser polishing different pulse duration (cw, ns, and fs), scan speed, repetition rate and average laser power were used and the impact on the material surface, the melt pool geometry, and microstructure was analyzed and correlated to the process parameters. When ultrafast laser radiation was used, the surface roughness increased at low scanning speeds, while for higher scanning speeds the Ra values were similar to the initial ones [12]. Better results were obtained by applying a cw laser source as shown in Figure 8 [13]. Laser polishing with 50 W average power and high scanning speeds reduced the surface roughness of the as-built AM

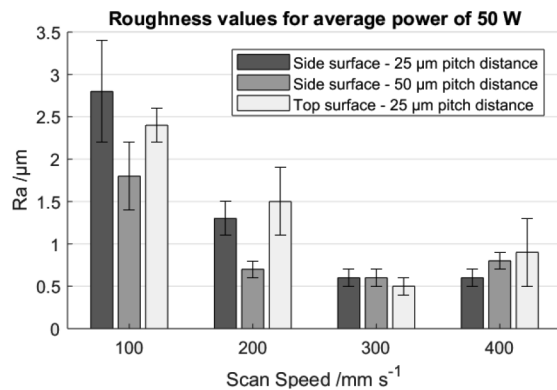


FIGURE 8. Roughness Ra as function of scan velocity and pitch distances for a continuous wave (cw) laser with 50 W average power (100 μm laser beam diameter) [13].

TABLE 1. Roughness Ra for top and side surfaces of an AM part as-built and after laser polishing with a cw laser with 50W average power and scan velocities of 300 and 400mm/s [13].

Speed	pitch	side		top
		25 μm	50 μm	25 μm
As-built		6.4 ± 0.8 μm	6.4 ± 0.8 μm	2.7 ± 0.6 μm
300 mm/s		0.6 ± 0.1 μm	0.6 ± 0.1 μm	0.5 ± 0.1 μm
400 mm/s		0.6 ± 0.1 μm	0.8 ± 0.1 μm	0.9 ± 0.4 μm

part ($2.7 \pm 0.6 \mu\text{m}$) to Ra values below $1 \mu\text{m}$ (for details see Table 1).

Metrology

In PAM² both in-process and post-process metrology is used. For in-process metrology both the use of optical meltpool monitoring and 3D geometrical measurements through the use of a compact focus variation system are envisioned.

For post-process metrology currently both micro-focus X-ray CT (computed tomography) and fringe projection profilometry (in combination with other form measurement techniques) are investigated. For both methods we aim to obtain high resolution images in order to assess the more precise AM parts that will be fabricated in the PAM² project.

X-ray CT

In X-ray CT, a sufficiently small focal spot size is necessary to analyse micro-features and structures [14]. One example where very high resolution is required is shown in Figure 9. The top part (Figure 9.a) of this figure shows a region of the reconstructed surface of a metal AM part obtained with high resolution CT in comparison with the same area inspected by confocal microscopy. The maximum height of texture surface in this case is in the range of $100 \mu\text{m}$, but very small features well below $100 \mu\text{m}$ are clearly visible. The bottom part (Figure 9.b) of the figure shows a cross sectional profile measured by X-ray CT and compared to the reference profile obtained using an imaging probing system after cutting and polishing the specimen. Some

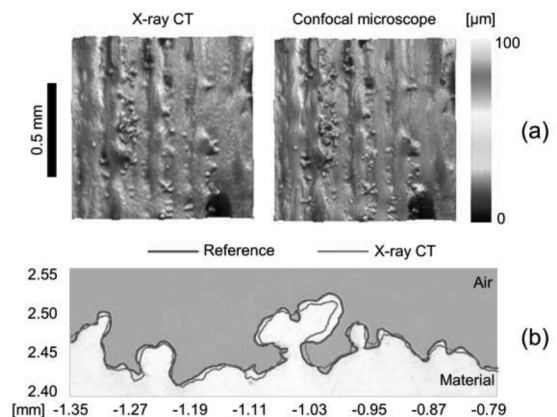


FIGURE 9. (a) Comparison of AM surface areal topographies measured by X-ray CT at high resolution and confocal microscopy; (b) comparison of an AM surface profile measured by X-ray CT at high resolution with the reference profile [15].

surface features, including undercuts (e.g. in the centre of Figure 9.b), are impossible to inspect with tactile or optical systems but can be inspected with CT. To be able to evaluate such features, it is necessary that the resolution is sufficiently high, otherwise the analysis suffers from loss of information and high uncertainties.

One of the main limiting factors of CT for high resolution inspection is the finite size of the focal spot i.e. where the electron beam impacts the target and heat and X-rays are generated. Thus in the last decade, much effort has been put into the reduction of the spot size. However, as existing standards [16] cannot fully cope with the achieved reduction in spot size, it is necessary to develop new methods and new standards to close this gap. A redesigned resolution test chart with feature sizes in the range of $36\ \mu\text{m}$ to $100\ \text{nm}$ (cf. Figure 10) has been developed to analyse the focal spot size. This range has been chosen to cover a broad range of already existing standards, but also to be able to measure resolutions which can be achieved with more recently developed X-ray sources (see e.g. [17]). The obtained values are additionally compared to already well established methods as the slanted edge method or JIMA resolution charts [18].

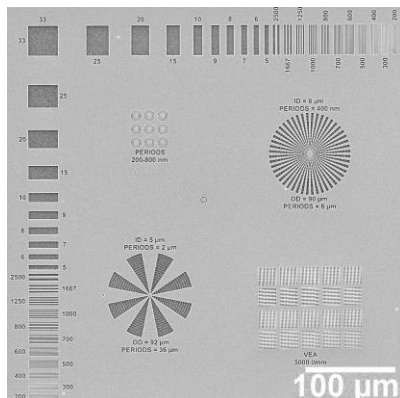


FIGURE 10. New designed test chart for micro- and nano-focus X-ray source evaluation.

Optical techniques

Additionally an accurate optical technique is being developed for form measurements of PAM² parts [19-21]. In the artificial intelligence (AI)-enhanced data-fused optical measurement framework that is being developed [19] for quick post-process 3D shape measurements, a combination of three techniques, namely fringe projection, photogrammetry and deflectometry, allows the measurement of multiple types of AM materials (both specularly and diffusely

reflective). The setup employs a high-resolution camera and an AI network which can quickly select the appropriate technique for each part of the areal measurement. This type of setup reduces the cost and complexity of the system by combining all three measurement systems into one framework while enabling an expanded material application range. We have been currently able to verify the technique by successfully fusing the measurements for a Ti6Al-4V, a Nylon 12 and a carbon fiber object (see Figure 11).

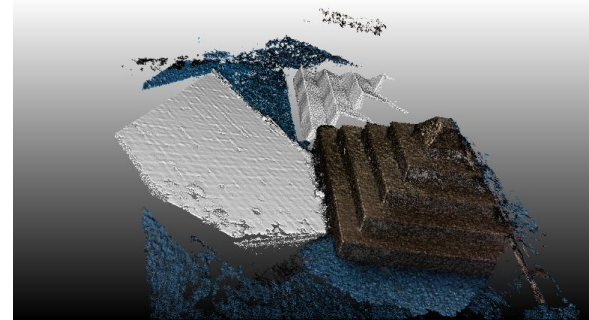


FIGURE 11. Fused photogrammetry, fringe projection and deflectometry data to optimally measure a Ti6Al-4V pyramid (bottom right) a Nylon 12 pyramid (top right) and a carbon fiber plate (middle left).

DISCUSSION and CONCLUSION

Ongoing research for each process stage of AM, going from the design stage to modelling, processing, post-processing and metrology, was presented. For each step we aim to progress the state of the art such that the final AM part precision and quality is improved. Topology optimization was executed in such a way that hot spots, and thus resulting AM part deformations, are avoided. Modelling is done by combining a full thermo-fluid dynamic model for accuracy and a lumped model for speed. This way complete parts can be simulated and possible issues can be detected before processing, again ensuring that final AM parts have the quality and precision that is needed. For evaluating the process, a novel benchmark part was made. This part also has advanced features (small pins and channels) that are beyond current machine capabilities, but which we hope to be able to fabricate with the new techniques to be developed in PAM². Combining laser additive with laser subtractive processing (either in-process or post-process) should enable us to go beyond the state-of-the-

art in terms of precision. Finally, if we make precise parts, we also need to be able to measure them precisely. In PAM² we use for example micro-focus X-ray CT to assess parts with micron-size features.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] Additive Manufacturing: Strategic Research Agenda, Consultation document prepared by the AM sub-platform; 2014.
- [2] PhD thesis Peter Mercelis, KU Leuven; 2007.
- [3] www.pam2.eu
- [4] Ranjan R, Yang Y, Ayas C, Langelaar M, Van Keulen F. Controlling local overheating in topology optimization for additive manufacturing. In: Proc of euspen SIG meeting: AM, Leuven, Belgium; 2017. p. 17-19.
- [5] Cheng B, Shrestha S and Chou K. Additive Manufacturing. 2016; 12:240-251.
- [6] Bayat M, Moshiri M, Mohanty S, Hattel J H. Multi-scale multiphysics simulation of metal powder bed fusion AM process and subsequent mechanical analysis. In: Proc. 12th International Seminar "Numerical Analysis of Weldability"; Graz, Austria; 2018.
- [7] De Baere D, Bayat M, Mohanty S, Hattel J H. Thermo-metallurgical modelling of the selective laser melting process chain. In: Proc. LANE; Fürth, Germany; 2018.
- [8] Moshiri M, Tosello G, Mohanty S A. New design for an extensive benchmarking of Additive Manufacturing machines. In: Proc. 18th euspen conference; Venice, Italy; 2018.
- [9] Metelkova J, Kempen K, Kinds Y, de Formanoir C, Witvrouw A, Van Hooreweder B. On the influence of laser defocusing in Selective Laser Melting of 316L, submitted to Additive Manufacturing.
- [10] Charles A P, Elkaseer A, Mueller T, Thijs L, Hagenmeyer V, Scholz S G. Investigation into the influence of process parameters on surface roughness of down-facing surfaces in Selective Laser Melting. In: Proc. WCMNM; Portorož, Slovenia; 2018.
- [11] Charles A P, Elkaseer A, Mueller T, Thijs L, Hagenmeyer V, Scholz S G. Effect of process parameters on dimensional accuracy of down-facing surfaces in selective laser melting of Ti6Al4V. In: Proc. ASPE summer topical meeting in AM; Berkeley, USA; 2018.
- [12] Solheid J, Seifert H J, Pflöging W. Laser-assisted post-processing of additive manufactured metallic parts. In: Proc. 18th Euspen conference; Venice, Italy; 2018. p. 275 - 276.
- [13] Solheid J, Seifert H J, Pflöging W. Laser surface modification and polishing of AM metallic parts. In: Proc. LANE; Fürth, Germany; 2018.
- [14] Zanini F, Carmignato S. Two-spheres method for evaluating the metrological structural resolution in dimensional computed tomography. Meas. Sci. Technol. 2017; 28: 114002. doi.org/10.1088/1361-6501/aa85b7.
- [15] Zanini F, Sbettega E, Sorgato M, Carmignato S. Accuracy of surface topography measurements performed by X-ray computed tomography on additively manufactured metal parts. In: Proc. 18th euspen conference; Venice, Italy; 2018. p. 465-466.
- [16] EN 12543 series (1-5):1999, Non-destructive testing. Characteristics of focal spots in industrial X-ray systems for use in non-destructive testing. European Committee for Standardization
- [17] <http://www.excillum.com/products-and-services/nanotube.html> (accessed 25.06.2018)
- [18] Baier M, Zanini F, Savio E, Carmignato S. A new conversion approach between different characterization methods to measure the spot size of micro computed tomography systems. In: Proc. 18th euspen conference; Venice, Italy; 2018. p. 445-446.
- [19] Stavroulakis P, Sims-Waterhouse D, Shaheen A, Catalucci S, Bointon P, Tzimiropoulos G, Leach R, Doyen E, Kong Y B, Leach R. External Shape Measurement for Industrial Applications using Artificial Intelligence and Optimised Data Fusion. In: Proc. Of Intelligent Systems Conference (IntelliSys); London, UK; 2018 (accepted).
- [20] Stavroulakis P I and Leach R K. Invited review article: Review of post-process optical form metrology for industrial-grade metal additive manufactured parts. Review of Scientific Instruments. 2016; 87(4): 0411011–04110115.
- [21] Stavroulakis P, Sims-Waterhouse D, Piano S, and Leach R. Flexible decoupled camera and projector fringe projection system using inertial sensors. Optical Engineering, 2017; 56(10): 1.

Geometric Dimensioning and Tolerancing in Additive Manufacturing

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INTRODUCTION

Geometric Dimensioning and Tolerancing (GD&T) standards and symbols are used in part design specification to convey allowable deviations that are acceptable during the manufacture of a part. ANSI Y14.5 and ASME Y14.5-2009 standard provide a detailed blueprint for analyzing and interpreting inspection data for various types of tolerances of manufactured parts. In recent years, with the increased interest in adapting additive manufacturing methods for the manufacture of metal parts, there is a need for understanding the relationship between GD&T callouts of a part and additive manufacturing process parameter decisions including build orientation, layer thickness and supports. Recently ASME has also released the Y14-46 draft standard for product definition for additive manufacturing. This presentation will describe methods developed at the University of Cincinnati for correlating and optimizing basic process parameters in additive manufacturing to achieve part GD&T callouts while minimizing build time, supports and energy consumed. The presentation will also discuss various adaptive modifications of STL files as well as new file formats for achieving part specific GD&T callouts.

METHODS

This presentation will focus on the following Additive Manufacturing specific GD&T related research performed at the University of Cincinnati:

1. Correlation of various GD&T errors with part geometry and part build orientation in AM. Correlation of part cusp error with local GD&T callout of part features. Determining optimal build orientation for achieving GD&T callouts while minimizing supports [1, 2, 9, 10].
2. Use of hierarchical data structures such as octrees, k-d trees and strip trees [4, 7, 13] to determine adaptive layering as well as identification of clustered adaptive layers for achieving part GD&T for a

given build orientation. Combined optimization of build orientation, adaptive layering and support contact minimization for achieving design tolerances [1].

3. Local and adaptive modification of STL files based on local geometry and chordal error for achieving part tolerances [3, 5].
4. Development of curved surface input file formats including Bezier and Steiner patches to replace STL file formats with a view to achieving part GD&T callouts [6, 8].
5. Prediction of GD&T errors based on shrinkage and thermomechanical analysis of the parts. Identification of optimal build orientation and slice thickness for achieving part tolerances based on part deformation prediction [12].
6. Minimizing GD&T errors and laser energy consumption in PBFAM process [11].

Each of these methods and associated results will be described briefly in the next few paragraphs:

Local and Adaptive Modification of Input Files for achieving Part GD&T callouts [3, 5, 6, 8]:

In [3, 5] adaptive densification of STL file is performed based on identifying the maximal local chordal error between an STL facet and the closest NURBS surface of the part. If the maximum chordal error for the STL facet exceeds a certain threshold, this facet is deleted and replaced by three other STL facets reducing the chordal error. Part tolerances are achieved by correlating the maximum chordal error of the facets with the local GD&T callout of the part feature and performing local adaptive recursive densification of the STL file. Figure 1 depicts the calculation of the error between the STL facet and the NURBS surface. Figure 2 presents the creation of new facets and figure 3 shows densification of the facets through each iteration

of the recursive algorithm. Improvements in profile error and other form errors using this approach ranged from 40% to 90%.

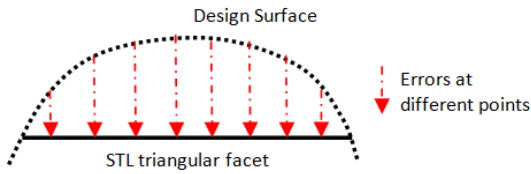


FIGURE 1: Error between STL facet and NURBS surface [5]

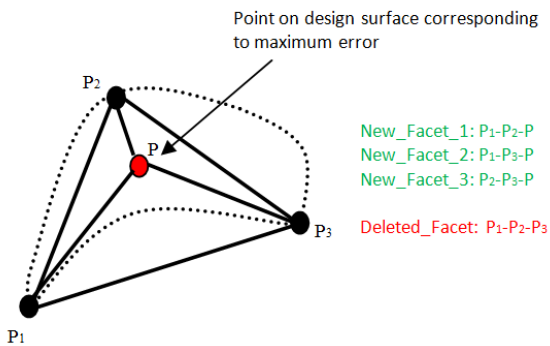


FIGURE 2: Creation of three new facets with reduced chordal error [5]

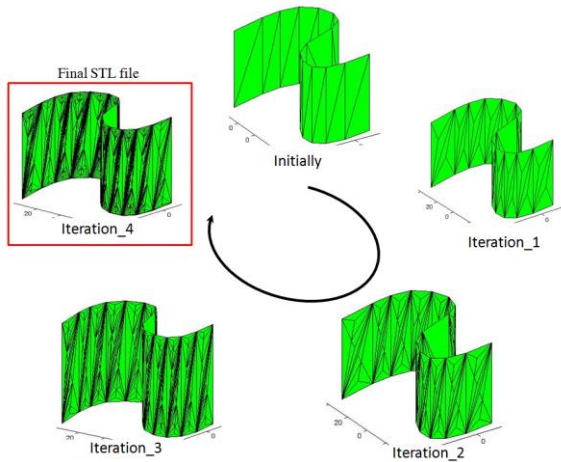


FIGURE 3: Iterative densification of STL facets [5]

In [8] the planar triangular facets of the STL file are replaced by bi-quadratic surfaces so as to align with the closest NURBS surface thus reducing the error between the CAD model and the biquadratic STL facets. An optimization routine is developed to obtain the control points of the biquadratic Bezier facets such that the error

between the closest surface and the biquadratic facet is minimized. The maximal error between the Bezier surface and the NURBS surfaces is correlated to the local GD&T callout of the part feature. This results in adaptive modification and conversion of selected STL facets to Bezier surfaces to meet the GD&T requirements of the local feature. Figure 4 depicts a linear edge Bezier patch that has replaced a planar triangular STL facet. Figure 5 presents the STL and the corresponding Bezier surface chordal error for a NURBS surface. Reduction in surface profile error and other form errors based on this approach ranged from 14% to 70% based on virtual part build and inspection.

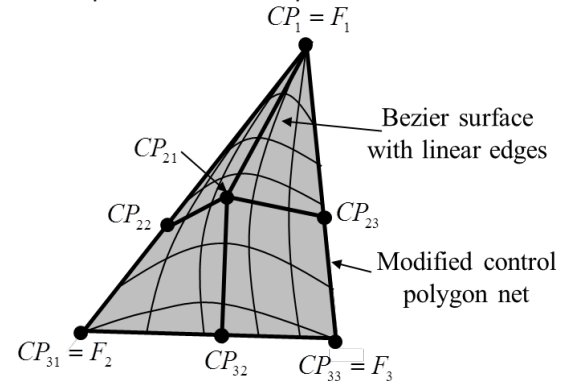


FIGURE 4: Biquadratic Bezier surface of STL facet [8]

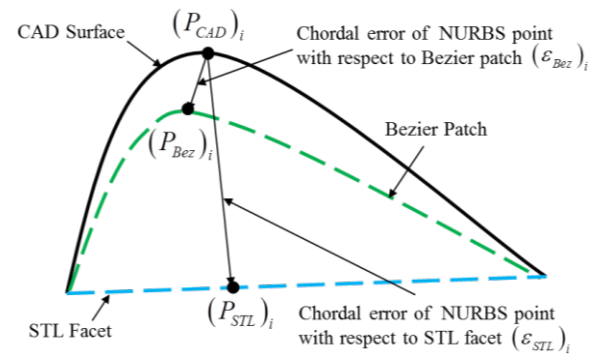


FIGURE 5: Chordal error between Bezier surface and NURBS [8]

Improving on this method, [8] presents an approach to replace the planar STL facets with a freeform Steiner patch that mimics the local CAD surface closely while taking into account the relationship between the local GD&T callout and the chordal error. The advantage of using a Steiner patch over Bezier surface is the fact that planar slicing of Steiner surfaces is a closed form solution allowing the generation of 2-D slice contours from the modified STL file quickly and

precisely. Figure 6 presents a Steiner patch representation of a free form surface and Table 1 presents a comparison of the chordal error between Steiner representation, STL and AMF file formats along with the number of facets.

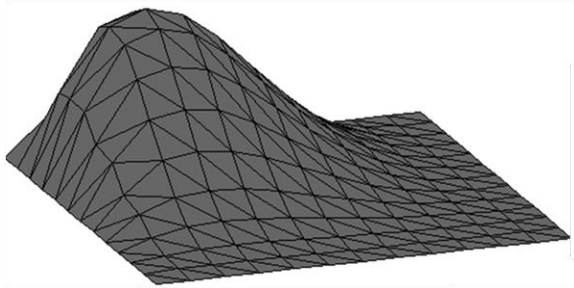


FIGURE 6: Uniform Steiner patch representation of STL [6]

Table1: Comparison between uniform Steiner, STL and AMF formats for Test Surface [6]

	Uniform Steiner	STL	AMF
# Facets	32	98	200
Chordal Error (mm)	0.01981	0.02092	0.02057

GD&T driven Adaptive Layering approaches [4, 7, 13]:

In [7] a Modified Boundary Octree Data Structure (MBODS) approach is used for discretizing the part model. Octrees are hierarchical spatial data structures that recursively divide the space of interest into eight octants. The octree model of the objects is recursively subdivided until the volumetric error between the NURBS surface and the octree cubes at the boundary nodes of the object is less than a certain threshold value. The final size of the boundary cubes that satisfy this threshold error value directly provides the thickness of the adaptive layer at that particular z level. This threshold error value is determined by relating it to the local GD&T callouts of the part model. Figure 7 presents the MBODS representation of a part model and the associated adaptive layers.

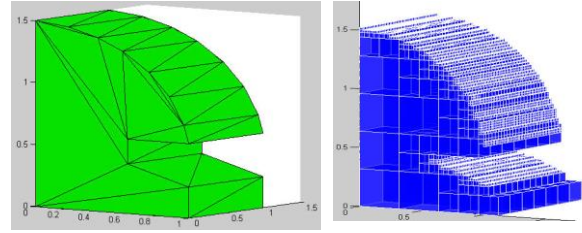


FIGURE 7: MBODS representation of part model [7]

In [13] and [4] a similar approach is adapted by representing the part and the boundary using k-d trees and strip trees respectively and deciphering the adaptive layers based on the relationships between volumetric errors at the boundary and the local GD&T callouts. The k-d tree adaptive layering [4] methods extends the approach to assign banded uniform layers at different z levels to achieve specific GD&T callouts for different features.

Optimal Build Orientation based on Correlation of Build Orientation and GD&T errors [1, 2, 9, 10, 11]:

In [9, 10] mathematical relationships between different form errors, layer thickness and build orientation are developed. Figure 8 shows a mapping of the cylindricity error and part build orientation for a given layer thickness.

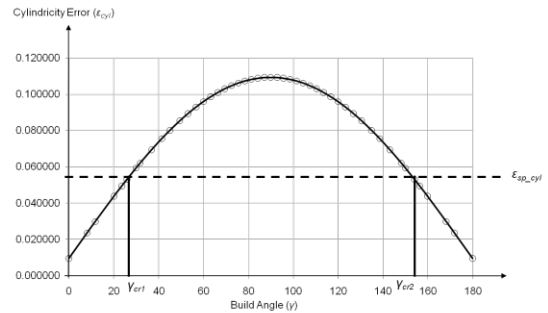


FIGURE 8: Cylindricity error vs Part Build Orientation [9,10]

The non-linear relationships between build orientation and form errors are then mapped to a one-dimensional line indicating feasible and infeasible regions of build orientation to achieve the desired tolerances. Figure 9 presents the one dimensional map of feasible build orientations for cylindricity error.

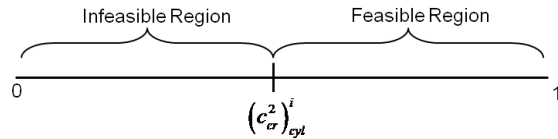


FIGURE 9: One dimensional map of cylindricity error [9, 10]

The problem is then formulated as a non-linear optimization approach for finding the optimal build orientation that minimizes all GD&T errors while also minimizing support structures. The volume of support structures is calculated using a voxel based approach. In [11] the problem is formulated to find the optimal build orientation to minimize the energy consumed as well as the part GD&T errors. In [1, 2] a combined optimization model is developed for minimizing GD&T errors while minimizing support volume and support contact area while maximizing support accessibility for quick removal during post processing. Figure 10 presents the optimal build orientation of a part with the support structures and support contact area highlighted.

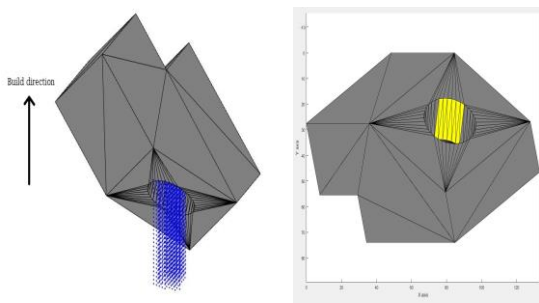


FIGURE 12: Optimal Build Orientation of part with support volume and contacts [1]

Correlation of thermal shrinkage and part deformation errors to GD&T errors [12].

In [12] a first principles birth and death thermal model is developed to simulate the laser travel and heat input in the PBFAM process. This is followed by a FEA model to simulate the thermomechanical deformations. These errors are then combined with the geometric errors to build a combined error model and correlate it to GD&T errors. Figure 11 shows a cylindrical part with flat and cylindrical features. Figures 12 and 13 show the plot of flatness and cylindricity errors on different faces of the part.

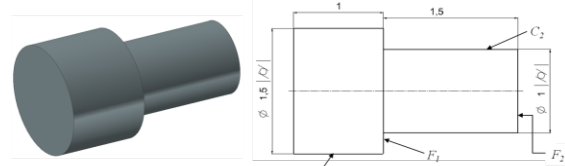


FIGURE 10: Part model with flat and cylindrical features [12]

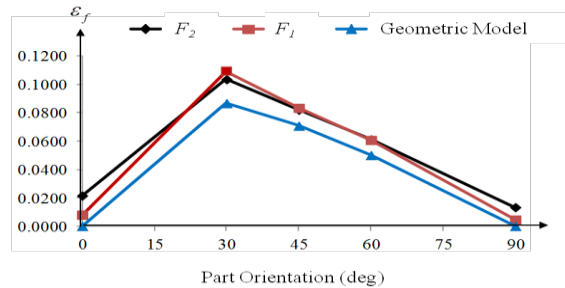


FIGURE 11: Flatness error of faces 1 and 2 of part model at different build orientations [12]

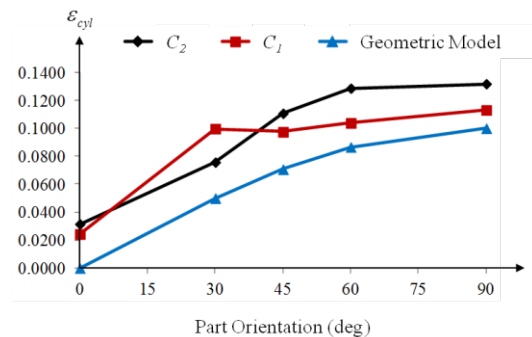


FIGURE 13: Cylindricity error of part model at different build orientations [12]

FUTURE WORK

A novel predictive part deformation and STL file compensation model using a proprietary neural network based approach has been developed at the University of Cincinnati. Part GD&T as well as surface roughness callouts are being incorporated into this model to provide a comprehensive approach for developing a geometry compensation model for “first part right” builds.

REFERENCES

- [1] Das, P. Mhapsekar, K., Chowdhury, S., Samant, R. Anand S., (2017), “Selection of build orientation for optimal support structures and minimum part errors in additive manufacturing: Computer Aided Design and Applications, 14:sup1, 1-13.

- [2] Das P. *, Chandran R. *, Samant R. *, Anand S., (2015), Optimum Part Build Orientation in Additive Manufacturing for Minimizing Part Errors and Support Structures, *Procedia Manufacturing Journal*, Vol 1, pp 343-354.
- [3] Zha W and Anand S., (2015), Geometric Approaches to Input File Modification for Part Quality Improvement in Additive Manufacturing, *Journal of Manufacturing Systems*, Vol. 20, Part 3, October 2015, pp 465-477.
- [4] Panhalkar, N., Paul, R. and Anand, S., (2014), "Error Minimization in Additive Manufacturing Processes using a k-d Tree based Adaptive Slicing Algorithm," *Journal of Manufacturing Science and Engineering*, 136(6).
- [5] Navangul, G., Paul, R. and Anand, S., (2013), "Error Minimization in Layered Manufacturing Parts by STL File Modification using a Vertex Translation Algorithm," *ASME Journal of Manufacturing Science and Engineering*., 135(3), pp. 031006/1- 031006/13.
- [6] Paul, R. and Anand, S., (2015), "Steiner Patch based Additive Manufacturing File Format," *Computer Aided Design (CAD) Journal*, Volume 63, June 2015, Pages 86–10.
- [7] Siraskar, N., Paul, R. and Anand, S., (2015), "A New Adaptive Slicing Algorithm in Additive Manufacturing Processes using a Modified Boundary Octree Data Structure," *Journal of Manufacturing Science and Engineering*, 137(1), 011007 (Feb 01, 2015) (11 pages).
- [8] Santosh, A. R. S., Paul, R. and Anand, S., 2013, "A New Additive Manufacturing File Format using Bezier Patches," *Proceedings of 41st NAMRC*, Madison, WI.
- [9] Paul, R. and Anand, S., (2014), "Optimization of Layered Manufacturing Process for Reducing Form Errors with Minimal Support Structures," *J Manuf Syst*, doi:10.1016/j.jmsy.2014.06.014
- [10] Paul R, Anand S. (2011), "Optimal Part Orientation in Rapid Manufacturing Process for Achieving Geometric Tolerances", *Journal of Manufacturing Systems*, 2011. Vol. 30, No. 4, pp 214-222.
- [11] Paul, R. and Anand, S., (2015), "Combined Error and Energy Minimization in Direct Metal Laser Sintering Process," *Rapid Prototyping Journal* , Vol. 21 Iss 3 pp. 301 – 312.
- [12] Paul, R., Anand, S. and Gerner, F., (2014), "Effect of Thermal Deformation on Part Errors in Metal Powder Based Additive Manufacturing Processes," *Journal of Manufacturing Science and Engineering* 136(3), pp. 031009-1-031000
- [13] Beltur B, (2016) "Adaptive Slicing in Additive Manufacturing using Strip Tree Data Structures" M.S. Thesis, 2016, University of Cincinnati.

TOWARDS DESIGN FOR PRECISION ADDITIVE MANUFACTURING: A SIMPLIFIED APPROACH FOR DETECTING HEAT ACCUMULATION

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INTRODUCTION

Selective laser melting (SLM) is a powder based metal additive manufacturing (AM) process that offers an unprecedented form freedom. Therefore, it is considered as an ideal enabling technology for topology optimized designs. The latter are typically complex in layout, but superior in performance. However, state of the art SLM machines cannot realize the dimensional accuracies required for high-precision components. One important issue leading to dimensional inaccuracy is the rapid heating-cooling of layers because of laser induced heat. As the laser melts the powder at the uppermost layer, heat diffuses towards the base plate which acts as a heat sink. It is well known that certain design features (e.g. overhangs and thin sections) can obstruct heat flow and cause local heat accumulation which leads to poor surface finish and undesired mechanical properties [1]. In literature, it has been suggested to use geometry based design guidelines which can sometimes become insufficient for avoiding heat accumulation [2]. Therefore, it would be beneficial to detect such features early during the design stage and thereby develop next generation topology optimization (TO) methods which could serve as an ideal design tool for precision AM industry.

In order to address thermal aspects of AM into a TO framework, an appropriate AM process model is required. This becomes problematic because a high fidelity AM process model is computationally very expensive and integrating it within a gradient-based TO framework becomes even more cumbersome [3]. Therefore, in this research, a physics based yet highly simplified approach is proposed in order to identify zones of heat accumulation in a given design. The computational gain offered by the simplification, makes it feasible to integrate the heat accumulation detection scheme within a TO framework.

The focus of this paper is on a simplified heat accumulation detection procedure, which is essential to ultimately realize a TO scheme accounting for thermal AM aspects. Aside from its use in a TO process, it can be independently used for analyzing AM designs, manual design improvements and determining optimal build orientations. In this paper, only the heat accumulation detection method is presented and its integration within a TO framework will be discussed in a separate paper.

There are two main simplifications made in this research which assists in reducing the computational cost associated with thermal analysis of AM designs. First simplification is to perform the thermal analysis only in the vicinity of the AM layer which is being deposited. This is motivated by the fact that the local geometry of only few previously molten layers have a significant effect on the *initial* cooling rate of the newly deposited layer [4]. The second simplification is to utilize a steady state thermal response, instead of transient, in order to predict heat accumulation. For this purpose, a physics based conceptual understanding is developed which enables estimation of spatially averaged transient thermal behavior of a local geometry just from its steady state response.

HEAT ACCUMULATION DETECTION: CONCEPTUAL UNDERSTANDING

It is well known that the topology of a structure has an influence on the heat flow inside it. Hence, different geometrical features in an AM design facilitate/obstruct heat flow during the AM process in a different manner. In this work we explore the possibility to approximately quantify, and hence compare, different geometries from the viewpoint of heat accumulation. For this purpose, first the concepts of thermal conductance and time constants are studied.

Thermal Conductance

Thermal conductance C is defined as the measure of a structure to conduct heat [5]. It is also equivalent to the reciprocal of thermal resistance. For an 1D case, thermal conductance is defined as

$$C = \frac{Q}{\Delta T} = \frac{k\mu}{L}, \quad (1)$$

where k represents thermal conductivity of the material, Q is the rate of heat transfer across a 1D rod with length L and cross-section area μ , and a steady state temperature difference of ΔT is achieved across the two ends of the rod. It is to be noted that thermal conductance is property of a structure as this definition addresses the geometry of the object by including the length and cross section parameters.

Figure 1 shows a 2D shape which is subjected to a heat load Q at its top edge while the bottom edges are fixed at temperature T_o with all other boundaries as thermally insulated. A steady state temperature field $T(x, y)$ is obtained which depends on described boundary conditions, material properties and topology itself. In order to quantify the conductive capability of this 2D geometry, we define the average thermal conductance as

$$\bar{C} = \frac{Q}{2(\bar{T}_{ss} - T_o)}. \quad (2)$$

Here, $\bar{T}_{ss}$ is the area averaged temperature which is calculated as

$$\bar{T}_{ss} = \frac{1}{A} \int \int T(x, y) dx dy, \quad (3)$$

where A is the area of the 2D object. Equivalently, in 3D a volume average is used. The boundary conditions used here are motivated by the AM process itself, where every design feature experiences a sudden heat load at the top and previously manufactured parts along with the base plate act as a heat sink. Also, powder surrounding the part has a very low thermal conductivity because of which the condition of thermal insulation has been considered for all other sides. The

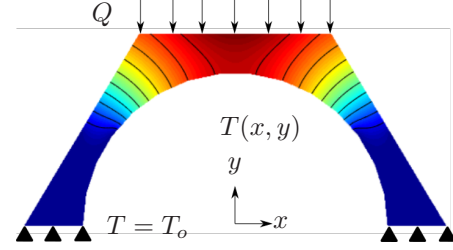


FIGURE 1. Steady state temperature field $T(x, y)$ for a 2D geometry with heat load Q acting on the top edge, bottom edges are at a fixed temperature T_o and all other edges are thermally insulated.

factor of 2 in the denominator of Eq. (2), is introduced in order to conform to the 1D definition of conductance given by Eq. (1), since for 1D case, $\Delta T = 2(\bar{T}_{ss} - T_o)$. Next, thermal conductance estimated from the highly simplified steady-state analysis is used to predict the heating/cooling rates of local topologies. This is motivated by the fact that post solidification cooling rates determine heat accumulation behavior and have a significant effect on micro-structural evolution [6]. In order to quantify heating/cooling rate we choose to study the time constant of the transient thermal response.

Thermal time constant

First, an expression is introduced for the average time constant in a 1D setting which is subsequently extended to 2D and 3D bodies.

1D heat transfer: Analytical study

Consider a 1D rod of length L subjected to heat flux ϕ at $x = L$ and ideal heat sink boundary condition at $x = 0$. The 1D heat equation reads

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (4)$$

Boundary conditions are given as

$$k \frac{\partial T}{\partial x} \Big|_{x=L} = -\phi, \quad (5)$$

$$T(0, t) = 0 \quad \text{for } t \geq 0, \quad (6)$$

and the initial condition is taken as

$$T(x, 0) = 0 \quad \text{for } x \in [0, L]. \quad (7)$$

Here, t is time, α is thermal diffusivity and x is position. Thermal diffusivity is given as $k/\rho c$ where ρ and c are mass density and specific heat, respectively. Using the method of separation of variables, the temperature distribution $T(x, t)$ as function of position and time is found and average temperature over the entire length of rod is calculated as

$$\bar{T}(t) = \frac{1}{L} \int_0^L T(x, t) dx. \quad (8)$$

Substituting the closed form solution of Eq. (4-7) in Eq. (8) and integrating, we find a converging infinite series given as

$$\bar{T}(t) = \frac{\phi L}{2k} \left[1 - \frac{32}{\pi^3} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{(2n-1)^3} e^{-\left(\frac{2n-1}{2}\right)^2 \frac{\pi^2 \alpha t}{L^2}} \right]. \quad (9)$$

If we consider only the first term of the series, spatially average temperature can be approximated as

$$\bar{T}(t) = \frac{\phi L}{2k} \left[1 - \frac{32}{\pi^3} e^{-\frac{\pi^2 \alpha t}{4L^2}} \right]. \quad (10)$$

Eq. (10) represents an exponential rise of $\bar{T}(t)$ for which time constant is given as

$$\bar{\tau} = \frac{4L^2}{\pi^2} \frac{1}{\alpha} = \frac{4L^2}{\pi^2} \frac{\rho c}{k}. \quad (11)$$

As expected, the average time constant is proportional to the heat capacity and inversely proportional to thermal conductivity.

Estimation of average time constant using 1D analogy

In this section, expression found for average time constant $\bar{\tau}$ for an 1D case is utilized for estimating that for 2D and 3D bodies. Figure 2 shows a 3D body (labeled as A) with volume V which is subjected to heat energy Q per unit time and bottom surface is fixed at $T = T_o$. We first define thermal capacitance for this body as

$$\lambda = V \rho c, \quad (12)$$

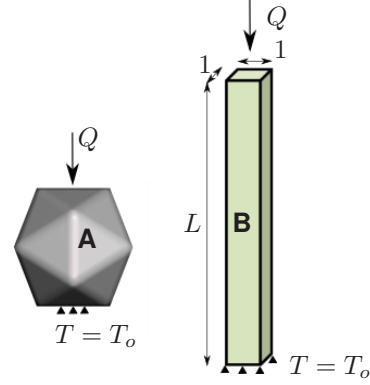


FIGURE 2. Equivalence of a 3D body (A) to a simplified body (B) with equal thermal capacitance and conductance.

analogous to the relation between conductivity and conductance c.f. Eq. (1). Next, we consider an imaginary body B with length L and unit width and depth such that both A and B have same thermal capacitance λ and conductance $\bar{C}$ when subjected to same boundary conditions. This is motivated by the fact that body B can be characterized by 1D understanding developed in the previous section and thermal equivalence between body A and B enables prediction of lumped thermal behavior of body A by computing that of body B. Equal thermal capacitance implies that both the bodies have same volume (assuming same specific heat and density) i.e.

$$L \cdot 1 \cdot 1 = V. \quad (13)$$

Next, equating the thermal conductance for both bodies and using Eq. (1) for body B, following expression can be written

$$\bar{C}_A = \bar{C}_B = \frac{k_B \mu}{L}, \quad (14)$$

where k_B is thermal conductivity of body B. As normal cross section area for body B is unity i.e. $\mu = 1$, k_B can be rewritten as

$$k_B = \bar{C}_A L. \quad (15)$$

Substituting found value of k_B from Eq. (15) into Eq. (11), and using Eq. (13), we find an estimate of average time constant $\bar{\tau}_e$ for body A as

$$\bar{\tau}_e = \frac{4}{\pi^2} \frac{V\rho c}{\bar{C}} = \frac{4}{\pi^2} \frac{\lambda}{\bar{C}}, \quad (16)$$

where subscript 'e' stands for estimated. Hence, Eq. (16) gives an expression which estimates average transient response just by using a steady state analysis. However, it is important to note that the described estimation gives only a lumped measure of the time constant averaged over the entire body and hence, does not provide local information within the considered domain. Therefore, we typically divide a design into a number of sub-geometries each of which is characterized by a $\bar{\tau}_e$ value. Also, in order to make this calculation invariant of domain size, a normalized time constant is considered as explained in the next section.

METHODOLOGY

The conceptual understanding described in the previous section is utilized for analyzing sub geometries within a given AM design. For this purpose, the spatial domain is divided into a number of cells, as shown in Fig. 3(a). An enlarged view of one of the cells within the geometry is separately shown in Fig. 3(b). Figure 3(c) shows the finite element mesh for this cell along with the boundary conditions which remains same as described for defining thermal conductance. A steady state thermal analysis is carried out using FEA by solving the heat equation given as

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0. \quad (17)$$

This gives a temperature field, as shown in Fig. 3(d). Average conductance $\bar{C}$ is calculated for each cell using Eq. (2) which is used for estimating the time constant using Eq. (16). The thermal time constant obtained from this analysis is utilized as a quantifier of heat accumulation for the geometry enclosed in that cell.

In order to verify the proposed formulation based on computationally cheap steady-state analysis, a transient heating response for each cell geometry is also computed through FEA which gives a temperature distribution as a function of time $T(x, y, t)$. A time step of 1s is considered for a total analysis time of 20s. Average temperature $\bar{T}(t)$ for each time step is calculated using Eq. (3)

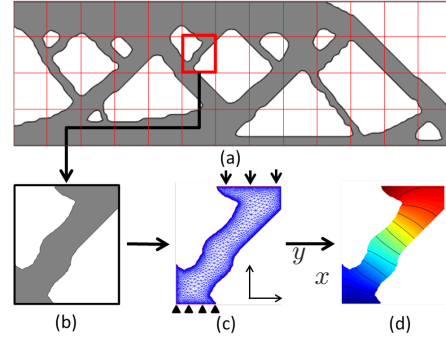


FIGURE 3. (a) A 2D geometry discretized into rectangular cells, (b) sample cell geometry, (c) meshing, (d) temperature field.

and fitted to the function

$$\bar{T}(t) = \bar{T}_{ss}(1 - e^{-\frac{t}{\bar{\tau}_r}}), \quad (18)$$

and a reference time constant $\bar{\tau}_r$ is determined for each cell according to the best fit. Reference and estimated time constants are represented as $\bar{\tau}_r$ and $\bar{\tau}_e$, respectively. In order to make the proposed methodology less sensitive to the cell size, normalized time constants are considered by dividing both time constants with that of a solid cell. Eq. (11) is used for calculating time constant for solid cell. Estimated $\bar{\tau}_e$ and reference $\bar{\tau}_r$ time constant maps for the design shown in Fig. 3(a) are presented in Fig. 4a and 4b, respectively. A cell-to-cell comparison is done between both the time constants, maximum and mean error is found to be 9.6% and 4.6%, respectively. Also, the steady state analysis is found to be 70% computationally cheaper than transient analysis. A schematic of the process for one of the cell geometry is presented in Fig. 5.

Concept of overlapping cells

The concept of dividing the design into overlapping cells has been utilized here in order to maximize the possibility of detecting heat accumulation zones. The design shown in Fig. 6 is first divided into a grid of $n_x \times n_y$ unit squares where n_x and n_y refers to number of grids in x and y directions, respectively. A cell is then defined with W_s unit squares in each direction as shown by cell A in Fig. 6. This cell is then moved by 1 unit in x and/or y directions in order to define other possible cell geometries labeled as B and C, respectively. The process

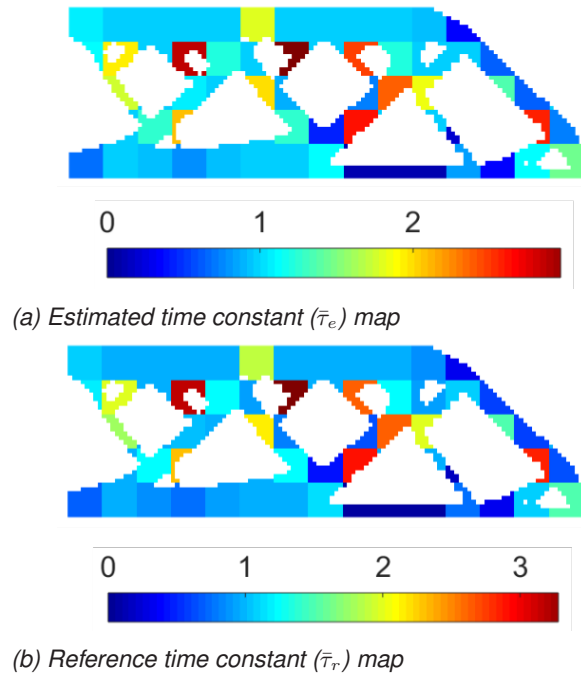


FIGURE 4. Time constant maps for geometry shown in Fig. 3(a).

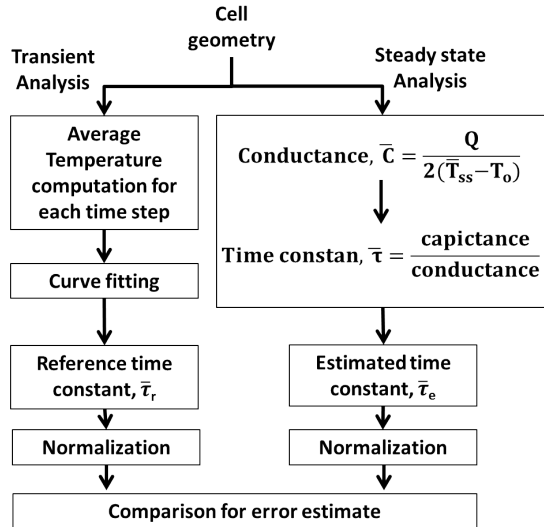


FIGURE 5. Flowchart for comparing reference $\bar{\tau}_r$ and estimated $\bar{\tau}_e$ time constant for each cell geometry obtained using transient and steady state thermal analysis, respectively.

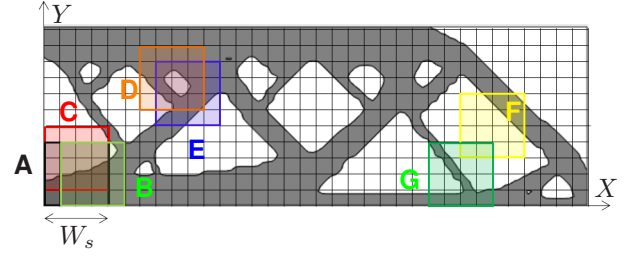


FIGURE 6. Definition of overlapping cells for heat accumulation detection.

is repeated such that all possible permutations $(n_x - W_s + 1)(n_y - W_s + 1)$ are considered for positioning the cell and defining cell geometries. A few of such possible cells are shown (labeled as A to G) in Fig. 6. The motivation behind considering all possible cell positions is to examine every possible geometry configuration (within the given grid resolution) for estimating highest time constants and hence, enhance the probability of heat accumulation detection.

NUMERICAL EXAMPLE

This section presents the implementation of the above discussed concepts for the purpose of detecting heat accumulation zones within the design shown in Fig. 6. Estimated time constants ($\bar{\tau}_e$) and reference time constants ($\bar{\tau}_r$) are calculated for each cell and Fig. 7a and 7b show the time constant map. Here, a cell overlaps its neighbors if its time constant is higher than that of adjacent cells. A cell-to-cell comparison between estimated and reference time constants is done and maximum and mean error is found to be 15.3% and 4.7% respectively. A computational gain of 75% is achieved by using steady state instead of transient analysis. Table 1 presents the parameters and material properties used for this analysis.

TABLE 1. Parameters for heat accumulation detection

Parameter	Value
Conductivity	7.1 W/m-K
Density	4.4×10^3 Kg/m ³
Specific heat	553 J/Kg-K
n_x	120
n_y	40
W_s	5

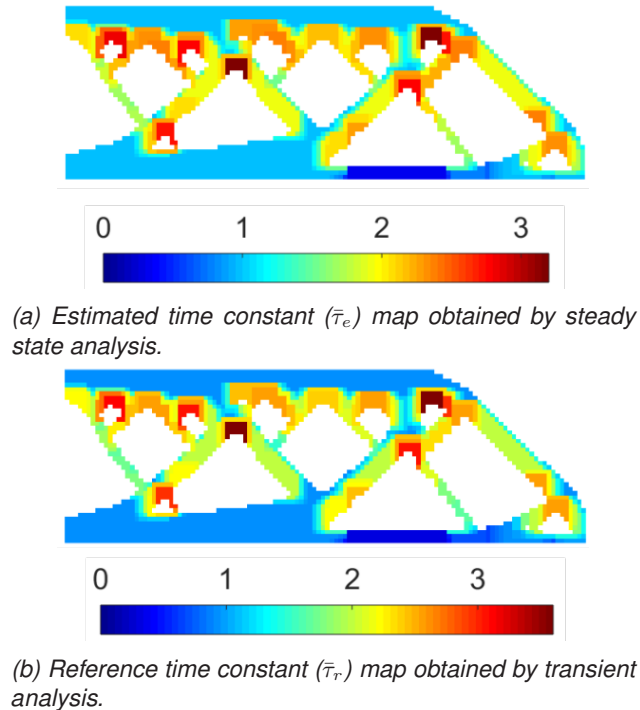


FIGURE 7. Time constant maps obtained by the heat accumulation scheme using the concept of overlapping cells.

OBSERVATIONS

As seen in Fig. 7, high time constants are recorded close to overhang surfaces. More importantly, it is noteworthy that Cells D, E, G and F shown in Fig. 6 have a cell geometry with 45° overhang angle. However, regions covered by Cells D and E tend to have a higher time constant than Cells G and F. This shows that heat accumulation for a design feature depends heavily on local geometry around its vicinity and purely geometric design guidelines of prescribing a limiting overhang value might become insufficient for preventing problems associated with local heat accumulation. This justifies development of design methods which can address physics of the manufacturing process in a more comprehensive manner and thus, can be advantageous for precision AM industry.

CONCLUSIONS AND FUTURE WORK

A simplification approach has been proposed for identification of heat accumulation zones in an AM part. The method employs steady state thermal analysis for predicting heat accumulation within local regions of a given AM design. Information from local geometries is then assembled and presented in form of a time constant map

which gives a pictorial representation of heat accumulation behavior for the entire structure. A transient analysis is also carried out to verify the developed analytical understanding and errors in estimation are reported along with achieved computational gain. It is found that heat accumulation tendency of a design feature is related to the local geometry around it and hence, a geometric design guideline only limiting the overhang angle can become insufficient in certain regions.

The computational advantage offered by the proposed method enables development of a physics based topology optimization method which would be beneficial for designing precision AM components. Next step for this research is to combine the developed method with density based topology optimization by penalizing design features which are prone to heat accumulation during each iteration.

REFERENCES

- [1] Sames WJ, List F, Pannala S, Dehoff RR, Babu SS. The metallurgy and processing science of metal additive manufacturing. *International Materials Reviews*. 2016;61(5):315–360.
- [2] Ranjan R, Yang Y, Ayas C, Langelaar M, Van Keulen F. Controlling local overheating in topology optimization for additive manufacturing. In: *Proceedings of euspen special interest group meeting: additive manufacturing*, Leuven, Belgium; 2017.
- [3] Schoinochoritis B, Chantzis D, Salonitis K. Simulation of metallic powder bed additive manufacturing processes with the finite element method: A critical review. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. 2017;231(1):96–117.
- [4] Keller N, Ploshikhin V. New method for fast predictions of residual stress and distortion of AM parts. In: *Solid Freeform Fabrication Symposium*; 2014. p. 1229–1237.
- [5] ASTM C168 - Terminology Relating to Thermal Insulation. ASTM International, West Conshohocken, PA, USA; 2013.
- [6] Kobryn PA, Semiatin S. Microstructure and texture evolution during solidification processing of Ti–6Al–4V. *Journal of Materials Processing Technology*. 2003;135(2-3):330–339.

MULTI OBJECTIVE DFAM CONSTRAINED TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTURING

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INTRODUCTION

Topology optimization is a class of numerical techniques for creating part geometries which provide maximal functional ability while maintaining given design constraints [1]. Topology optimization has existed as a design tool for decades, but has not attained widespread utilization until recent years for various reasons. One particular reason is that the designs which are output by a basic topology optimization algorithm are often very complex in shape and are difficult to manufacture by traditional means.

However, it is possible to modify topology optimization algorithms to produce geometries with greater manufacturability [2]. Typically, the algorithm is modified by means of adding a “filter,” which effectively takes any configuration of material and modifies it in such a way that the configuration becomes manufacturable. Different filters can result in geometries with different properties. One example would be a filter which enforces that the geometry be prismatic, which can be used for designing parts to be manufactured by extrusion. Another example is a filter which prevents undercut features in a single draw direction for casting processes.

With the advancement of additive manufacturing technologies, complex topology optimization designs have become much easier to manufacture. Often times, a non-filtered topologically optimized geometry can be additively manufactured, whereas the same geometry would be impossible to manufacture traditionally. However, there are still limitations on what is achievable with current manufacturing processes, and further limitations on what is practical. DFAM guidelines have been identified [3] which outline design features which should be avoided for successful additive manufacturing of parts. Incorporating such guidelines into the topology optimization procedure can take full advantage of utilizing this method for additive manufacturing.

The Center for Global Design and Manufacturing (CGDM) at the University of Cincinnati is working on several optimization and computational approaches relevant to additive manufacturing. The following is a description of topology optimization methods which are specifically tailored for designing structurally and thermally efficient geometries for additive manufacturing. This includes reduction of unfriendly features, distribution of lattice structures within the part design space, and design of lattice unit cells with favorable mechanical properties.

SUMMARY OF METHODS

Integrated additive manufacturing topology optimization routines have been created for avoidance of the thin features and support structures. Since very thin features appearing in a layer slice are difficult to accurately manufacture, a filter has been developed within topology optimization to eliminate these features [4]. Support structures may be required for producing overhanging surfaces, which is inefficient and wasteful. A multi-objective cost function [4] and penalty function filter [8] were developed to minimize support volume requirements of a part.

Since lattice structures are a popular design feature unique to additive manufacturing, algorithms have been created to maximize the potential of these structures. Gyroid lattices have several properties which make them desirable for additive manufacturing and have been implemented previously within a topology optimization routine [5]. A representative volume element based topology optimization procedure has also been created which considers a unit cell's unique strength properties at variable densities to optimize the distribution of lattices [6]. Additionally, unit cells have been designed using topology optimization which achieve low coefficient of thermal expansion by utilizing two different materials while also maintaining high stiffness [7].

Thin Feature Prevention [4]

A filter was created which looks at finite elements of the topology optimization mesh on a layer-by-layer basis and penalizes elements which are considered to be members of a thin feature. A user defined radius is supplied which represents the minimum radius of a circular feature in order to not be considered “thin.” For every element in the mesh, the algorithm checks if it is contained within a circle of that radius which contains solid elements. If it is not contained within the circle, then that element should not be solid because it would be part of a thin feature. The end result of the optimization is a geometry which has maximum stiffness to a load while also ensuring that thin layer-wise features are reduced.

The mathematical description of the filter is shown in equations (1) and (2), where x_{TR} is the post-filtered density of an element, $\tilde{x}$ is the pre-filtered density, n_e is the number of elements in the primary neighborhood of the element, w is a user defined weightage of the filter, and n_2 is the number of elements in the secondary neighborhood. Visualization of the neighborhoods used in this filter are presented in Figure 1.

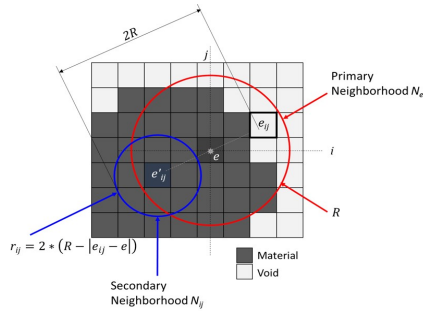


FIGURE 1. Element with thin region neighborhood [4].

Comparison of results between the unconstrained and constrained optimization for a cantilever beam case study can be seen in Figure 2 and Table 1.

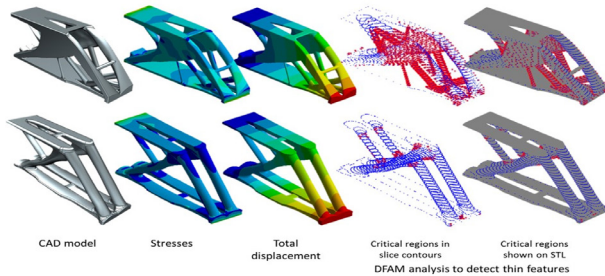


FIGURE 2. Comparison of topologically optimized geometries without (top) and with (bottom) thin feature constraint [4].

$$x_{TR} = w * \frac{\sum_{a=1}^{n_e} F(\tilde{x}_{ij})_a}{n_e} * \tilde{x} + (1 - w) * \tilde{x} \quad (1)$$

$$F(\tilde{x}_{ij}) = \tilde{x}_{ij} * [\tilde{x}_{ij}] + [\tilde{x}'_{ij}] * \frac{\sum_{n_2} \tilde{x}'_k}{n_2} * [1 - \tilde{x}_{ij}] \quad (2)$$

TABLE 1. Results with/without thin feature constraint.

Metrics	Unconstrained	Constrained
Manuf. Score	0.0834	0.8925
Part Volume	12124.59 mm ³	10254.22 mm ³
Max Disp.	4.7x10 ⁻⁵ m	5.8x10 ⁻⁵ m
Max Stress	16 MPa	20 MPa

Support Structure Reduction [4, 8]

A multi-objective cost function was used to simultaneously minimize the compliance of the designed part to a specified load as well as minimize the support volume which would be required for manufacturing the part. The compliance calculation is standard to structural topology optimization, and a new support volume calculation function was created for this objective function. The weightages of the compliance and support values can be varied by a designer to allow a trade-off between the two.

Equation (3) is the weighted multi-objective optimization function, where $c(\tilde{x})$ and $s(\tilde{x})$ are the standard compliance and new support volume functions, C_1 and S_1 are normalization values, and w_1 and w_2 are weightages. The support volume function is expanded upon in equations (4) and (5), where $\tilde{x}$ are the densities of the cubic elements and v is the volume of the elements. $\tilde{x}_{m,i}$ is the maximum density of the 5 elements in the support region of element i , as shown in Figure 3. γ_{xyz} is a function which is calculated recursively in a columnar manner starting from the substrate, as in Figure 4.

$$f(\tilde{x}) = w_1 \frac{c(\tilde{x})}{C_1} + w_2 \frac{s(\tilde{x})}{S_1} \quad (3)$$

$$s(\tilde{x}) = \sum_{i \in D} \tilde{x}_i (1 - \tilde{x}_{m,i}) * \gamma_{xyz} \quad (4)$$

$$\gamma_{xyz} = \begin{cases} \tilde{x}_{xyz} (1 - \tilde{x}_{xy(z-1)}) \sum_{k < z} [(1 - \tilde{x}_{xyk}) v_{xyk} - \gamma_{xyk}] & \text{if } z > 1 \\ 0 & \text{if } z = 1 \end{cases} \quad (5)$$

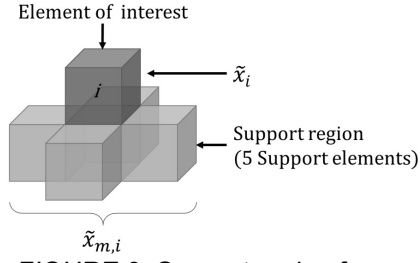


FIGURE 3. Support region for an arbitrary element [4].

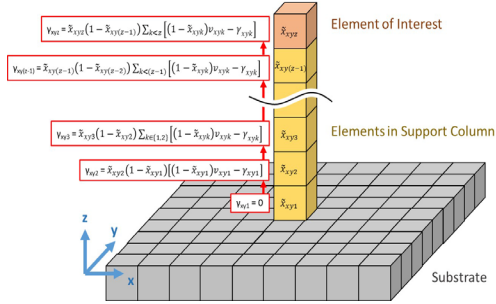


FIGURE 4. Recursive calculation of support volume requirement [4].

Comparison of results of constrained and unconstrained optimization are shown in Figure 5 and Table 2.

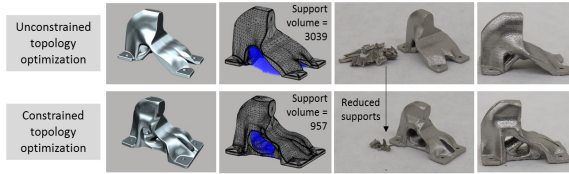


FIGURE 5. Geometry comparison with/without constraint [4].

TABLE 2. Results with/without support constraint.[4]

Metrics	Unconstrained	Constrained
Support Vol.	3039 mm ³	957 mm ³
Part Volume	8196.47 mm ³	8331.84 mm ³
Max Disp.	1.02x10 ⁻⁵ m	1.10x10 ⁻⁵ m
Max Stress	210.5 MPa	209.0 MPa

An alternative filter based method [8] has been implemented to reduce support structures. The principle method is to identify support requiring finite elements and reduce the weightages of such elements so that the optimization model is inclined to treat that particular element as void as the iteration progresses. Three scenarios identified in the design domain where one must

consider the surrounding elements for it to be treated as supports are represented in Figure 6.

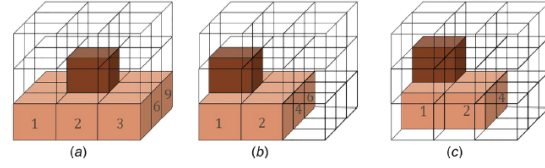


FIGURE 6. Support elements for (a) nonboundary element, (b) boundary element with six bottom elements, and (c) boundary element with four bottom elements [8]

The objective function is a classic compliance minimization with a volume constraint. An exponential function [8] is used to penalize the element according to its support requirement. The mathematical representation of the penalty function is given by equation (6).

$$Penalty = H - \frac{H-L}{e^{S(\sigma_e-1)}+1} \quad (6)$$

This function defined in equation (6) is designed to assign high penalty threshold, H if support coefficient σ_e is greater than 1, or else, a low penalty threshold L is allocated.

The topology optimization and FEA results obtained by implementing this support minimization algorithm is shown in Figures 7 and 8 respectively. The comparison with conventional topology optimization is listed in Table 3.

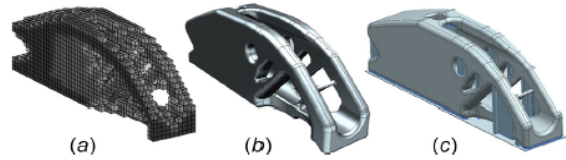


FIGURE 7. (a) Results for constrained topology optimization process, (b) 3D model for design, and (c) support structures [8]

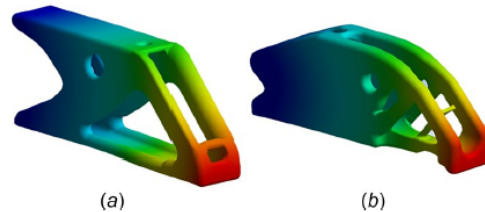


FIGURE 8. Deformation results for (a) standard top. opt. and (b) constrained top. Opt [8]

TABLE 3. Results with/without support constraint.[8]

Metrics	Unconstrained	Constrained
Support Vol.	2909.7 mm ³	767.66 mm ³
Part Volume	3416 mm ³	4014 mm ³
Max Disp.	4.02x10 ⁻³ mm	6.2x10 ⁻³ mm
Max Stress	453 MPa	301.0 MPa

Graded Gyroid Lattice Design [5]

A scheme has been developed which can take results obtained by density-based topology optimization and smoothly incorporate gyroid lattice structures into the part design. By using lattice structures, lightweight parts can be achieved and the gyroid lattice is self supporting in nature which prevents the need for additional support material to be used during manufacture of internal geometries.

The parametric function in equation (7) defines the boundary of the gyroid geometry, where L is the size of a unit cell and t is the parameter which controls the volume fraction of the gyroid.

$$F(x, y, z) = \sin\left(\frac{2\pi x}{L}\right) \cos\left(\frac{2\pi y}{L}\right) + \sin\left(\frac{2\pi y}{L}\right) \cos\left(\frac{2\pi z}{L}\right) + \sin\left(\frac{2\pi z}{L}\right) \cos\left(\frac{2\pi x}{L}\right) = t \quad (7)$$

For a given geometry, the density distribution as obtained from a SIMP topology optimization procedure is used as the basis for defining the value of parameter t as a function of position in space. This defines the surface of the graded lattice design. A cantilever beam example is shown in Figure 9 and Table 4.

TABLE 4. Gyroid lattice results.

Metrics	Solid	Lattice
Unit Cell Size	-	3.3 mm
Volume Fract.	37.5%	26.7%
Max Disp.	1.29x10 ⁻⁵ m	1.73x10 ⁻⁵ m
Max Stress	.948x10 ⁻² MPa	.660x10 ⁻² MPa

FIGURE 10. Lattice structures and displacement plots for (top) SIMP and (bottom) RVE optimized geometries with X shaped lattice[6].

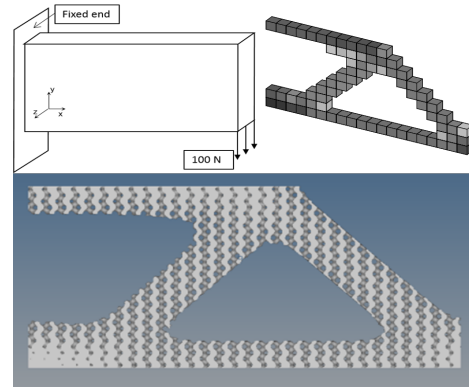


FIGURE 9. Gyroid lattice created for cantilever beam case study[5].

Graded Lattice Optimization with RVEs [6]

A new material property interpolation scheme was created for optimizing distribution of density for functionally graded lattices. Lattice structures typically exhibit non-isotropic strength properties which vary non-linearly with density. This new interpolation scheme uses representative volume elements (RVE) in the topology optimization scheme which are tailored to the strength properties of the specific lattice type which is to be used. The resulting geometries significantly outperform geometries which are obtained using arbitrary interpolation schemes such as SIMP.

Since the proposed interpolation scheme is not arbitrary, the intermediate density RVEs are able to more accurately capture the deformation characteristics of the lattice as compared to the SIMP interpolation scheme, and more optimal lattice density distributions can be found during the optimization procedure.

A cantilever beam with a hole case study was analyzed for an X shaped 2D lattice using both the SIMP and proposed RVE methodologies. The penalization value in SIMP was set to 1 in order to allow for intermediate density material to exist for lattice replacement. Images of the lattice geometry for both methodologies is shown in Figure 10, along with results in Table 5.

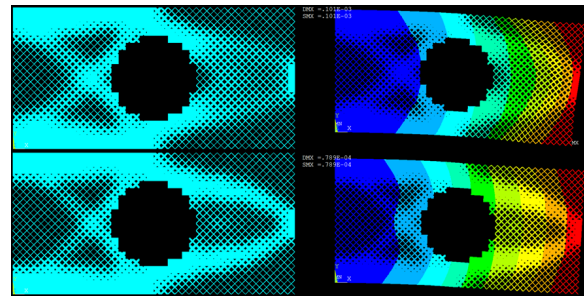


TABLE 5. SIMP vs. RVE lattice results.

Metrics	SIMP	RVE	% diff
Compliance (N.m)	9.74×10^{-2}	7.74×10^{-2}	-20.5%
Max Disp. (m)	1.01×10^{-4}	7.90×10^{-5}	-21.8%

Low CTE Lattice Structures [7]

In applications where a part experiences high magnitude fluctuations in temperature, thermal expansion can negatively affect the performance of a part. By using multiple materials of differing CTE, it has been shown that a unit cell can be created which has relatively low CTE while maintaining structural strength. Using a multi-material topology optimization scheme, lattice structures can be generated which have low effective CTE as well as high effective strength. Additionally, The lattices can be tailored for thermal conductivity thus allowing the lattice to behave either as a thermal inulator or conductor depending on the application.

An example of a lattice generated with this method is shown in Figure 11. Material properties of the two materials as well as the properties of the lattice are presented in Table 6.

TABLE 6. Material properties of materials and lattice structure.

Properties	Invar	Struc. Steel	Result
Young's Modulus (GPa)	145	210	60
CTE (1/K) ($\times 10^{-6}$)	1.2	12	6.3
Conductivity (W/m.K)	12	36	8.9
Poisson's Ratio	.3	.3	-
Vol Fraction	.3	.3	-
Bulk Mod (GPa)	103	150	-

FUTURE WORK

Other DFAM guidelines exist for which topology optimization filters and methodologies have not been created. Research is ongoing to address some of these guidelines, and further work is required to combine existing and future topological optimization procedures into a single workflow, allowing design of parts for additive manufacture which optimally address a wide array of guidelines simultaneously.

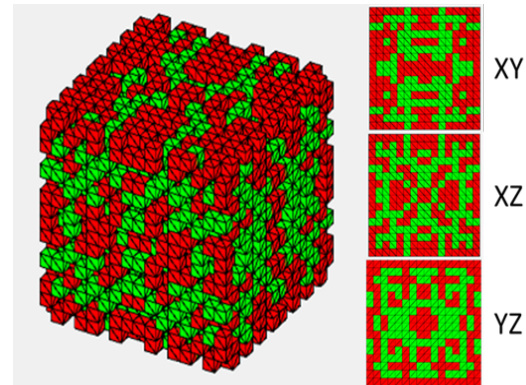


FIGURE 11. Low CTE, low conductivity lattice unit cell with side views[7]

REFERENCES

- [1] Bendsoe, M.P., and Sigmund, O. *Topology Optimization: Theory, Methods and Applications*. Springer Berlin (2004).
- [2] Zhou, M. et al. "Progress in Topology Optimization with Manufacturing Constraints." *AIAA/ISSMO*. 2002-5. Atlanta, GA, September 4-6, 2002.
- [3] Gibson, I., Rosen, D.W., Stucker, B. "Design for Additive Manufacture" *Additive Manufacturing Technologies*. Springer. New York (2010): pp. 283-314.
- [4] Mhapsekar, K. et al. "Additive Manufacturing Constraints in Topology Optimization for Improved Manufacturability." *JMSE* 140(5) (2018).
- [5] Zhang, B. et al. "Design of Variable-Density Structures for Additive Manufacturing Using Gyroid Lattices." *IDETC/CIE. DETC2017-68047*: pp. V004T05A015. Cleveland, OH, August 6-9, 2017.
- [6] Matthew McConaha MS Thesis, 2018, University of Cincinnati, Cincinnati, OH
- [7] Vysakh Venugopal Thesis, Ongoing MS Thesis 2018, University of Cincinnati, Cincinnati, OH
- [8] Ranjan R. et al. "Integration of Design for Manufacturing Methods with Topology Optimization in Additive Manufacturing." *JMSE* 139(6) (2017)

TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTURING: FULLY PRINTABLE COMPLIANT MECHANISMS

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INTRODUCTION

Driven by a continuous demand for, e.g., smaller transistors, higher throughput, or higher accuracy, the performance of precision machines is under constant pressure. Consequently, new manufacturing methods such as additive manufacturing are adopted to manufacture complex components with superior functionality or performance over their subtractively manufactured counterparts. However, conventional design methods often fail to use additive manufacturing to its full extend. Therefore, topology optimization has become a popular design method for additive manufacturing, in order to fully utilize the available design freedom.

Topology optimization is a technique that optimizes a design for a given objective and constraints, by adjusting its shape and topology [1]. It can, for example, minimize the mass of a certain part, while maintaining a given minimum stiffness. The resulting designs often are geometrically complex, and thus can only be produced by additive manufacturing. However, a large amount of support material is frequently required during printing, which is costly to build and remove. The necessity for support material originates from the presence of down facing or overhanging surfaces of a part, which is an inherent limitation of the layer-by-layer manufacturing process. As each layer needs a certain connection to the previous layer, the distance with which subsequent layers can extend orthogonal to the building direction is limited. This is specified by the critical overhang angle α_{oh} [2].

It is thus attractive to include an overhang limitation as a design rule into topology optimization, such that the resulting designs are readily printable. This saves both material and labour cost,

and enables a shorter time-to-market. Moreover, without the overhang constraint, regions in the design could emerge where the support material cannot be removed after the build. In such cases including the overhang limitation in the design is a must. Several studies have presented an overhang constraint for density based topology optimization [3, 4, 5], however those schemes were either highly non-linear, increasing the total number of iterations [3], not fitted for unstructured meshes and with overhang angle dictated by the aspect ratio of the elements [4], or not robustly satisfying the overhang limitation [5]. Therefore, we implement the methodology as described in [6, 7] to include the overhang limitation into topology optimization in an efficient, mesh independent manner with a continuously variable overhang angle, utilizing front propagation. In this study, this methodology is applied to a detailed 3D design of a compliant mechanism.

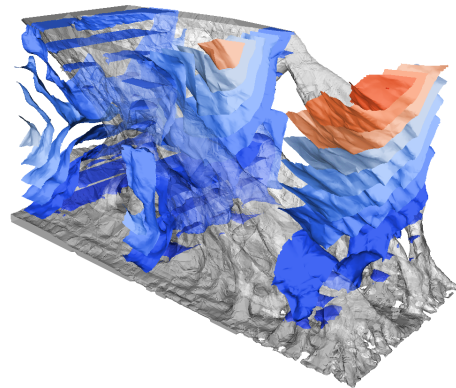


FIGURE 1. Front propagation around a given geometry used for overhang detection. Colors indicate front arrival time.

FRONT PROPAGATION BASED OVERHANG DETECTION

In order to constrain overhang below a certain α_{oh} within topology optimization, regions that violate the overhang limitation need to be identified in a differentiable manner, such that the sensitivity information can be fed back to the optimization algorithm. For that purpose, we use front propagation [8] as an approximate model for the printing process. Front propagation algorithms are well established and numerically inexpensive. Furthermore, they are differentiable, and evaluating the sensitivities can be done in an adjoint manner.

The printing process can be seen as an evolving front, where with every layer the front propagates. In order to detect regions that violate the overhang limitation, an anisotropic speed profile is used for the front propagation. The speed profile is chosen such that the front propagates similar to the printing process when it is travelling in directions above the minimum overhang angle. However, when the front propagates below this critical angle, the speed is decreased. This then enables the detection of overhanging regions as regions where the front is delayed. Additionally, the amount of delay gives an indication of the severity of the overhang violation, which is used by the optimization algorithm to steer the optimization such that critical regions are properly supported by structural material. A depiction of a front propagation through a geometry can be seen in FIGURE 1.

A 2D version of this algorithm has been presented in [6], and an extension to 3D including a parallelization of the front propagation has been presented in [7]. The front propagation is calculated efficiently using the Ordered Upwind Method [9], an algorithm with computational complexity $O(N \log N)$. The algorithm is parallelized using a domain decomposition approach based on the method presented in [10], but adapted for anisotropic front propagation. The reader is referred to [6] and [7] for details on the front propagation method.

COUPLING WITH TOPOLOGY OPTIMIZATION

The overhang limitation is implemented into the topology optimization as a filter: for a given design the filter returns only the printable regions. This overhang filter is applied on the filtered density field (FIGURE 2). The front propagation is

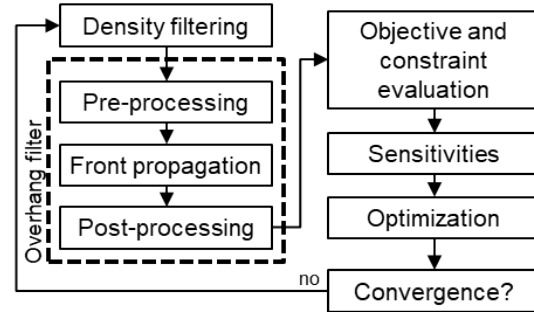


FIGURE 2. Flow chart of the topology optimization procedure with overhang filter. The overhang filter is inserted after the density filtering step.

coupled with the topology optimization by scaling the propagation speed with the density field. As such, the front will propagate at regular speed through dense regions, but will be slowed down in void regions. For this, a scaling field is defined as

$$\phi(\mathbf{x}) = v_{\text{void}} + (1 - v_{\text{void}})\rho^*(\mathbf{x}), \quad (1)$$

where ρ^* is the filtered density field, and v_{void} is the minimum propagation speed in void regions. The scaling field ϕ is calculated in the pre-processing step, depicted in FIGURE 2.

Next, the front propagation is performed which gives an arrival time field T . This is then transformed back to a printable density field ξ in the post-processing step, using the following relation:

$$\xi(\mathbf{x}) = 2^{-\kappa(\tau(\mathbf{x}))}, \quad (2)$$

$$\tau(\mathbf{x}) = T(\mathbf{x}) - T_{\text{ref}}(\mathbf{x}), \quad (3)$$

where the field $\tau(\mathbf{x})$ represents the delay of the propagated front with respect to a reference arrival time field T_{ref} . This reference field contains the arrival times if the part would have been completely printable. Consequently, the regions where $\tau(\mathbf{x}) = 0$ are printable, and will have a density of one ($2^0 = 1$), while regions with increasing delay will have a density ranging between 0 and 1. The parameter κ controls how aggressively overhanging regions are suppressed. Finally, the printable density field ξ is obtained, and used for the evaluation of the objective and constraints.

RESULTS

The front propagation based overhang filter is demonstrated on a topology optimization of a compliant mechanism, with domain and boundary conditions displayed in FIGURE 3. The objective is to transform a vertical force into a horizontal

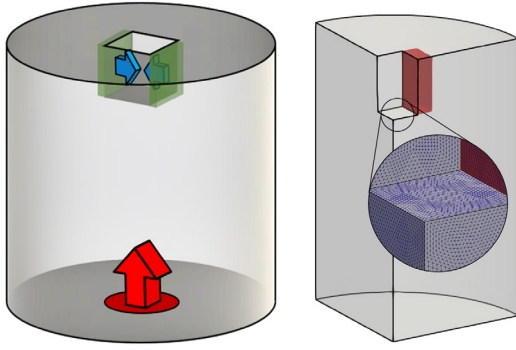


FIGURE 3. Compliant mechanism test case. A force is applied on the bottom with the objective to move the two green surfaces in the top cavity inwards, to provide for a gripping motion. The side of the cylinder is mechanically clamped. One quarter of the domain is simulated, as displayed on the right. Furthermore, A detail of the numerical mesh is displayed in the right image.

motion, in order to generate a gripping motion inside a cylindrical domain. Such a gripper could for example be used to pick and manipulate small objects in production equipment.

During the optimization, the normal displacement of the gripping surfaces due to a load f_1 on the bottom surface is maximized. A relatively small penalty on the volume is added to the objective, in order to remove non-functional material from the final topology. Because compliant mechanisms tend to form weak links between structural members to mimic pin joints, a constraint that limits the maximum compliance of the mechanism is included. For this constraint, the load f_2 is a combination of the original load f_1 , and a normal force on the gripper surface. As such, the constraint guarantees a minimum stiffness between the gripper surfaces, the loading surface and the boundary of the domain. This leads to the following minimization problem

$$\begin{aligned} \min_{\rho} \quad & \frac{1}{f_0} \int_{\Gamma_1} -\mathbf{u}_1 \cdot \mathbf{n} dA + \frac{\alpha}{V_{\text{tot}}} \int_{\Omega} \rho dV, \\ \text{s.t.} \quad & \mathbf{K} \mathbf{u}_1 = \mathbf{f}_1, \\ & \mathbf{K} \mathbf{u}_2 = \mathbf{f}_2, \\ & \int_{\Omega} \mathbf{f}_2 \cdot \mathbf{u}_2 dV \leq c_{\text{max}}, \\ & 0 \leq \rho \leq 1, \end{aligned} \quad (4)$$

where f_0 is a normalization factor, V_{tot} the total volume, Γ_1 the gripper surface, and penalty factor

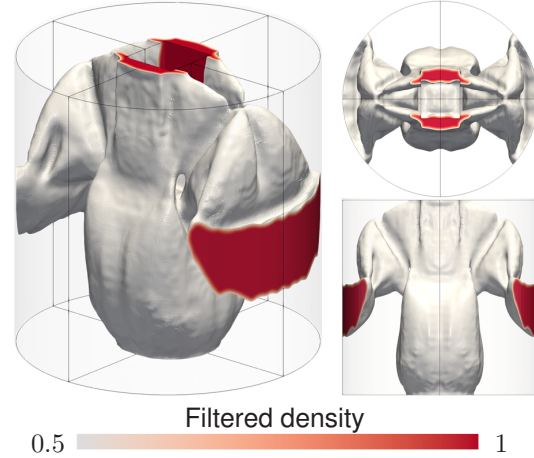


FIGURE 4. Optimized gripper topology without overhang filter. The color represents the filtered density values, and the isosurface for $\rho = 0.5$ is given. A similar color scale and isosurface is used for the remaining images.

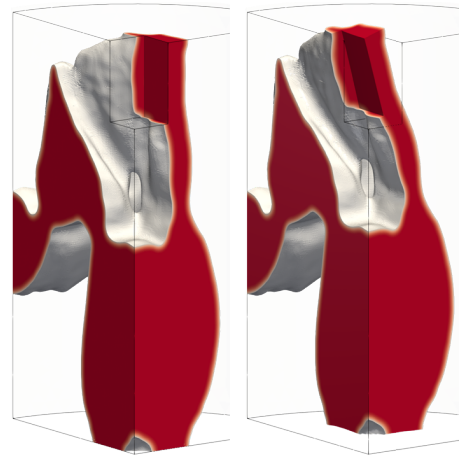


FIGURE 5. Quarter section of the topology undeformed (left) and deformed (right).

α is chosen equal to 1.

Elements with $\rho = 1$ are given a Young's modulus of $E = 1 \text{ GPa}$, and for void elements this is $E = 1 \cdot 10^{-4} \text{ GPa}$. Furthermore, a density filter is used with a radius of $5h$, where h is a typical element size. The Method of Moving Asymptotes [11] is used to optimize the topology, and the FEM problem is solved in parallel using PETSc [12]. Due to the symmetry of the case, only a quarter of the cylinder is simulated, as shown in FIGURE 3. The domain is meshed with roughly $9 \cdot 10^6$ tetrahedral elements containing $2 \cdot 10^6$ vertices.

Without overhang filter, the mechanism displayed

in FIGURE 4 is obtained. The gripping surface is attached to the domain boundary by two rigid bodies connected with leaf spring like structures. When the gripping surface is pushed upwards by the actuator, this leaf spring structure pulls it inwards, providing a gripping motion (FIGURE 5). However, this topology is not printable without support structures, as shown in FIGURE 6. The supports are costly to manufacture, and also difficult to remove as some of the supports are in small cavities. Therefore, the same case was optimized with the proposed overhang filter with $\alpha_{oh} = 45^\circ$, resulting in the topology displayed in FIGURE 7. In order to prevent supports underneath the attachment to the boundary, a slightly different structure is developed, and a connecting beam is added to make this structure printable without supporting structures. The resulting deformation when applying f_1 is shown in FIGURE 8. The overall objective decreases by 15% compared to the non-overhang-constrained topology optimization. Generally, the addition of the overhang filter reduces the performance, dependent on how close to printable the original design is.

Both optimizations were terminated after 50 iterations. The overhang filter was gradually introduced from iteration 10 to iteration 20, by interpolating between the filtered density field and the printable density field. Both the FEM problem and the front propagation were solved in parallel using 20 cores (Intel Xeon E-2630v4). Per iteration, a single FEM solve took roughly 20 seconds, while the front propagation was performed in approximately 6 seconds. Since three FEM solves

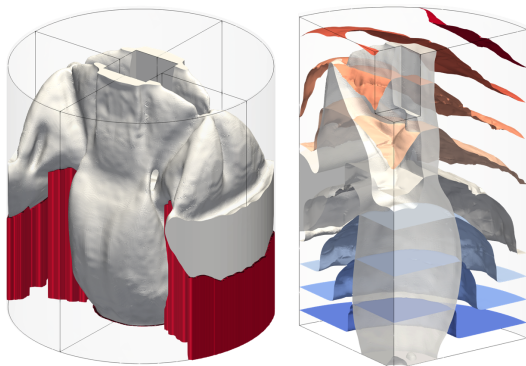


FIGURE 6. Left: the required supports to print the optimized topology in red. Right: front propagation through the optimized topology. In the printable regions of the topology, the front stays level with the base plate.

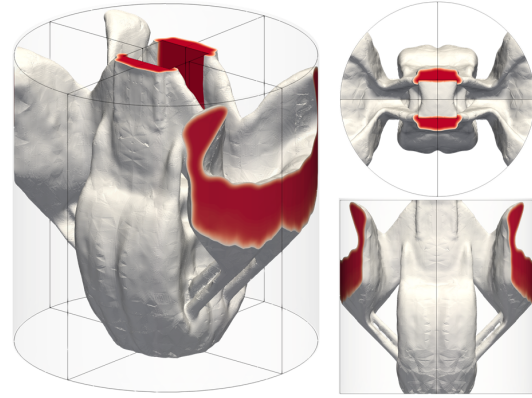


FIGURE 7. Optimized gripper topology including overhang filter. The topology is printable in the displayed configuration without the need for supports.

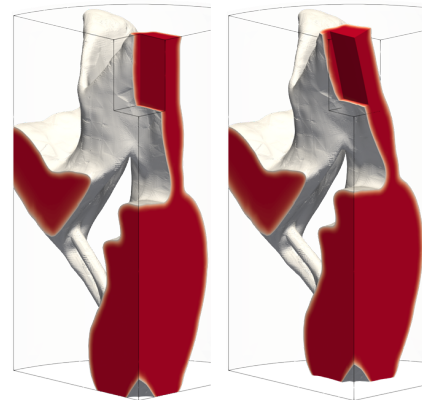


FIGURE 8. Quarter section of the printable topology undeformed (left), and deformed (right).

are required for the presented problem (objective, objective adjoint, and constraint evaluation), the front propagation does not add a significant computational cost to the topology optimization.

CONCLUSION

In this paper we have demonstrated the application of the front propagation based overhang filter, presented in [6, 7], on a compliant mechanism. With overhang filter, the topology is significantly changed to adapt to the printability criterion. While being printable without supports, the objective decreased with 15% compared to the non printable design.

Due to the continuous nature of the front propagation, the unstructured mesh presented no

problem for the overhang filter. This greatly contributes to the practical applicability on CAD based domains, instead of academic block domains with regular meshes. Although not demonstrated in this paper, the continuous nature also allows for overhang angles other than 45° .

Finally, the overhang filter made no significant contribution to the overall computational cost, due to its parallelization and the fast solution methods available for anisotropic front propagation.

In future work, the accessibility of supports should be investigated. For some applications, the presence of supports is acceptable and one would therefore only want to prohibit overhang in internal regions, where the supports cannot be removed.

REFERENCES

- [1] Bendsoe MP, Sigmund O. Topology Optimization: Theory, Methods and Applications. Engineering online library. Springer; 2003.
- [2] Thomas D. The development of design rules for selective laser melting. University of Wales; 2009.
- [3] Gaynor AT, Guest JK. Topology optimization considering overhang constraints: Eliminating sacrificial support material in additive manufacturing through design. Structural and Multidisciplinary Optimization. 2016;54(5):1157–1172.
- [4] Langelaar M. Topology optimization of 3D self-supporting structures for additive manufacturing. Additive Manufacturing. 2016;12:60–70.
- [5] Qian X. Undercut and overhang angle control in topology optimization: A density gradient based integral approach. International Journal for Numerical Methods in Engineering. 2017;Nme.5461.
- [6] van de Ven E, Maas R, Ayas C, Langelaar M, van Keulen F. Continuous front propagation-based overhang control for topology optimization with additive manufacturing. Structural and Multidisciplinary Optimization. 2018 May;57(5):2075–2091.
- [7] van de Ven E, Maas R, Ayas C, Langelaar M, van Keulen F. 3D overhang control for topology optimization with additive manufacturing; 2018. Manuscript in preparation.
- [8] Sethian JA. Level set methods and fast marching methods: evolving interfaces in computational geometry, fluid mechanics, computer vision, and materials science. vol. 3. Cambridge university press; 1999.
- [9] Sethian JA, Vladimirsky A. Ordered upwind methods for static Hamilton–Jacobi equations: Theory and algorithms. SIAM Journal on Numerical Analysis. 2003;41(1):325–363.
- [10] Yang J, Stern F. A highly scalable massively parallel fast marching method for the Eikonal equation. Journal of Computational Physics. 2017;332:333–362.
- [11] Svanberg K. The method of moving asymptotes – a new method for structural optimization. International journal for numerical methods in engineering. 1987;24(2):359–373.
- [12] Balay S, Abhyankar S, Adams MF, Brown J, Brune P, Buschelman K, et al.. PETSc Web page; 2018. <http://www.mcs.anl.gov/petsc>. Available from: <http://www.mcs.anl.gov/petsc>.

Micro-Powder Bed Fusion (μ -PBF) – Extremely high resolution for small-scale applications

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INTRODUCTION

High-tech applications in the field of micro technology call for enhanced miniaturization of products coupled with improved functionality and individualization. In order to expand the capabilities of Laser-Powder Bed Fusion (L-PBF), research projects at Fraunhofer ILT have led to a significant increase of detail resolution and surface quality of small-scale parts. The procedure it has developed, Micro-Powder Bed Fusion (μ -PBF), enables parts to be manufactured with structure widths of down to 30 μm and surface roughness of $S_a = 1.3 \mu\text{m}$. Unlike conventional L-PBF, μ -PBF uses very fine powders combined with thin powder layers, a small laser spot size and modulated laser radiation. Producing parts under such conditions was made possible with a modified Realizer SLM-50 L-PBF machine.

STATE OF THE ART

Due to the increasing demand for small, highly complex components that benefit from the geometric freedom of additive manufacturing, several research facilities are currently working on the development of high-precision L-PBF processes.

Researchers at the Institute of Production Management, Technology and Machine Tools (PTW) of the Technical University of Darmstadt, Germany are working on micro Selective Laser Melting (μ -SLM) using an EOSINT $\mu 60$ machine (Yb laser, 38 W, 1062 nm, 30 μm spot diameter). With optimized parameters, PTW researchers were able to build dense components ($\rho_{\text{rel}} \geq 99 \%$) using 316L powder with an average particle size of $d_{50} = 3.62 \mu\text{m}$. A minimum surface roughness of $R_a = 1.69 \mu\text{m}$, measured on vertical surfaces, was achieved. For these results, a layer thickness of 7 μm was selected and the laser was operated in continuous wave (cw) mode [1], [2]. Researchers at Mittweida University of Applied Sciences are also working on μ -SLM. In addition to improving surface quality and detail resolution, they are also focusing on increasing the build rate [3]. The Mittweida μ -SLM approach was

developed to process fine molybdenum and tungsten powder ($d_{90} \leq 15 \mu\text{m}$) into parts with a minimum structure width of 60 μm and a surface roughness of $R_z = 35 \mu\text{m}$. Layers of 10 μm thickness were fused by a 400 W continuous wave laser focused on a 40 μm spot diameter [4]. In further studies, Mittweida University combined a pressure-assisted powder coating mechanism with a custom-made polygon scanner to achieve fast scanning velocities for higher build rates (high-rate μ -SLM). In this case, molybdenum and 316L powders ($d_{50} = 2.4 \mu\text{m}$) were fused with scanning velocities between 50 m/s and 200 m/s. Layer thicknesses of 1 - 20 μm were used to achieve minimum structure widths down to 35 μm and surface roughnesses down to $R_a = 3 \mu\text{m}$. In this process, however, the powder was only sintered and not completely melted [5].

μ -PBF APPROACH AT ILT

The μ -PBF approach developed at Fraunhofer ILT differs from the previously described μ -SLM approaches with regard to the laser's mode of operation. In contrast to the conventional L-PBF process and the other μ -PBF approaches, ILT does not operate the laser in continuous wave (cw) mode but in pulsed wave (pw) mode. In this mode, thin melt tracks can be generated whose widths approximately correspond to the diameter of the focused laser beam. This approach enables a significant increase in detail resolution and surface quality. It is particularly useful for filigree component structures, such as sharp corners or thin walls.

Aside from changing the laser's mode of operation, ILT has based its μ -PBF approach on downscaling the L-PBF process [6],[7]. Conventional L-PBF typically uses powders with particle sizes of 15 to 50 μm , layer thicknesses of 30 to 50 μm , and laser spot diameters of 50 to 700 μm [8]. In contrast, ILT's μ -PBF approach uses powders with smaller particle sizes ($d_{90} \leq 10 \mu\text{m}$), smaller layer thicknesses (10 μm) and smaller laser spot diameters (25 μm).

MATERIALS

Materials that have been successfully processed with ILT's μ -PBF approach and their particle size are shown in Table 1.

Available μ -PBF materials	
Material	d_{90}
316L	$\leq 10\text{ }\mu\text{m}$
IN718	$\leq 15\text{ }\mu\text{m}$
IN625	$\leq 10\text{ }\mu\text{m}$
Mar247	$\leq 15\text{ }\mu\text{m}$
Ni-Ti	$\leq 10\text{ }\mu\text{m}$
Au	$\leq 10\text{ }\mu\text{m}$
AlSi10Mg	$\leq 15\text{ }\mu\text{m}$

Table 1: Powder materials that were already processed with ILT's μ -PBF approach.

The small powder particles tend to form agglomerations that result in limited powder flowability. This complicates powder deposition and makes it hard to obtain homogeneous powder layers. However, homogeneous powder layers are crucial for achieving low surface roughnesses.

Figure 1 shows an example of the particle shape and size distribution of the Ni-Ti powder used to build the components shown in Figures 4 and 5.

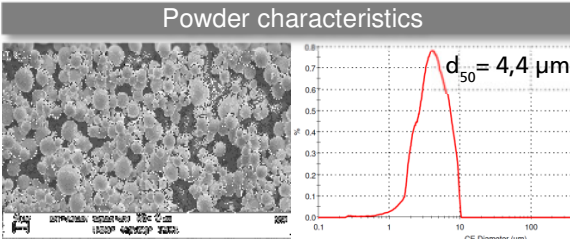


Figure 1: SEM image and particle size distribution of the applied nickel-titanium alloy.

The powder consists of spherical particles with a mean diameter of $d_{50} = 4.4\text{ }\mu\text{m}$. Since the particles agglomerate easily, a special powder coating unit was designed at ILT for use in μ -PBF machines. The unit can create a desired powder bed with each of the powder materials listed in Table 1.

EQUIPMENT

The μ -PBF process was performed on a modified SLM-50 machine from Realizer (Figure 2).

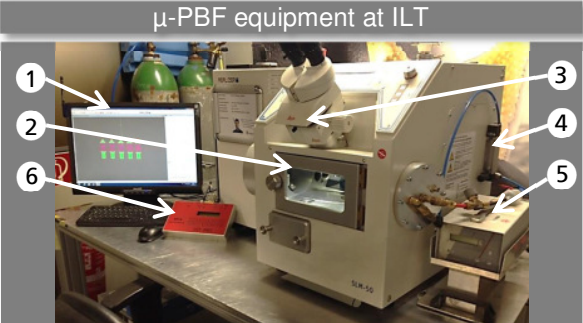


Figure 2: Modified SLM-50 machine from Realizer.

The machine is controlled by a desktop computer with the control software “ROperator” (1), which provides full access to the process parameters. The process chamber (2) includes a powder-deposition wiper mechanism and a build platform with diameter of 70 mm, both of which render the system suitable for jewelry and dental applications. For process observation, a microscope with a magnification of 6.25 to 40x is attached to the top of the process chamber (3). The system is equipped with an air-cooled single-mode ytterbium fiber laser yielding a maximum output power of 120 W in continuous wave (cw) mode. The focus spot diameter is approximately 25 μm [9].

For μ -PBF, the machine was modified: First, a custom-made vibrating unit was added, which supports powder deposition and enables even powder spreading for particle sizes $d_{90} < 10\text{ }\mu\text{m}$. Second, an altered inert gas supply (4), controlled with an oxygen sensor BA 4510 from Bühler GmbH (5) was applied for improved inert gas atmosphere of $\text{O}_2 < 30\text{ ppm}$. Third, a laser controller LCT3001 provided by MCA was applied in order to trigger the laser signal, yielding modulated laser radiation [10].

In Figure 3 a schematic illustration of the trigger signal is illustrated. The laser on/off signal is

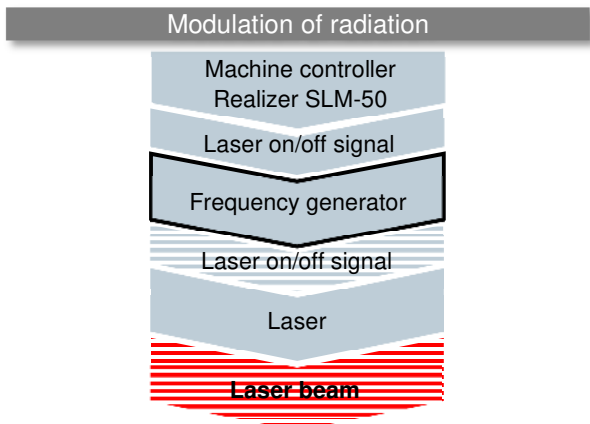


Figure 3: Schematic illustration of the trigger signal for establishment of modulated laser radiation.

provided by the machine control and forwarded to the frequency generator, which provides the trigger signal, superimposed with the initial on/off command of the machine control. The triggered on/off command then yields modulated laser radiation, which is guided through the optical components to the material interaction zone.

ACHIEVEMENTS

At Fraunhofer ILT, the μ -PBF process was developed in-depth for a variety of powder materials. For example, Ni-Ti shape memory alloys can be processed with very high detail resolution and low surface roughness. The following figures show components that demonstrate the capabilities of the process in terms of detail resolution, surface roughness and integrated functionality.

Detail resolution

Figure 4 shows a stent with a complex hollow tube design (4 mm diameter and 12 mm height) that was built using a Ni-Ti shape memory alloy with a particle size of $d_{50} = 4.4 \mu\text{m}$. Single-track experiments were performed to develop a process parameter set that resulted in small wall thicknesses down to $32 \mu\text{m}$. It was found that when laser pulse length and laser power were reduced, so too was the melt track's width.

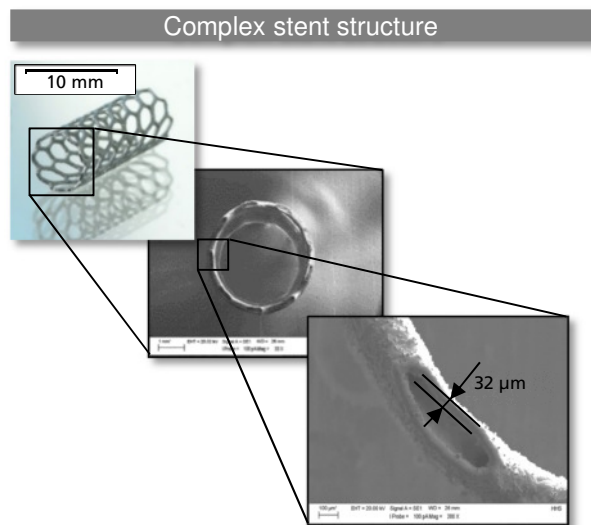


Figure 4: Stent with complex hollow tube structure made from Ni-Ti. The minimal structure size is about $32 \mu\text{m}$.

Surface roughness

To increase the surface quality, the process parameter set was further optimized. It was possible to identify parameter combinations that yielded a surface roughness of $S_a = 1.3 \mu\text{m}$.

In particular, the use of pulsed wave (pw) laser radiation proved beneficial to reducing surface roughness. Short pulse lengths in combination with low scanning velocities had the most significant impact on surface quality.

The resulting parameter set can be used to build small complex structures with low surface roughness.

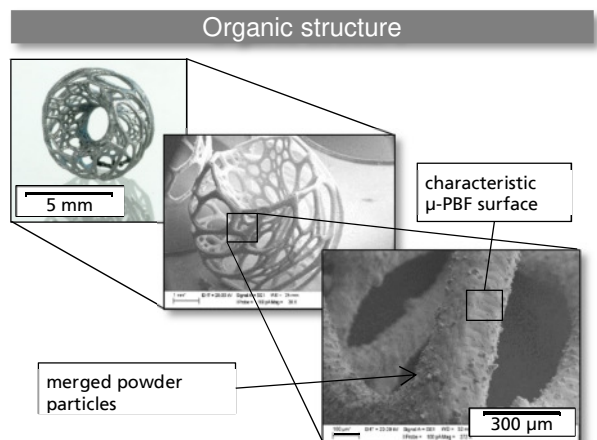


Figure 5: Organic μ -PBF structure indicating high detail resolution and only few sintered powder particles. Made from Ni-Ti.

Figure 5 shows an organic structure made from Ni-Ti. The magnified SEM image shows the surface structure of the component. Even in overhang areas, only a small amount of sintered powder particles was observed.

Integrated functionality

Components with integrated functionality (e.g., planetary gears or articulated joints) can be manufactured since the μ -PBF process can produce small-scale parts with very high detail resolution and surface quality. Such parts can be produced with tolerance deviations as low as approx. 20 μ m.

Figure 6 shows a monolithic demonstrator that was manufactured in one piece without subsequent assembly.

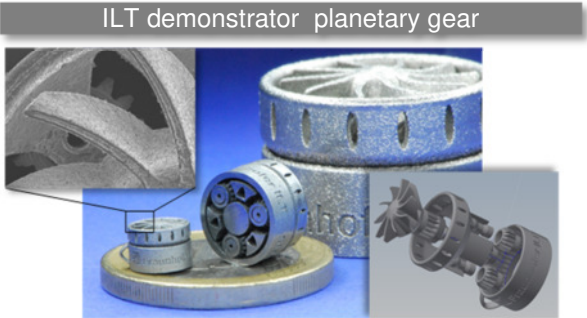


Figure 6: Functioning planetary gear, manufactured in one piece without the need for assembly. Made from 316L.

The demonstrator consists of six parts that can be moved relative to each other. When the upper ring is moved, the translation of the planetary gears causes the fan to rotate at three times the speed.

Figure 7 shows a SEM image of the bottom of the helical planetary gear.

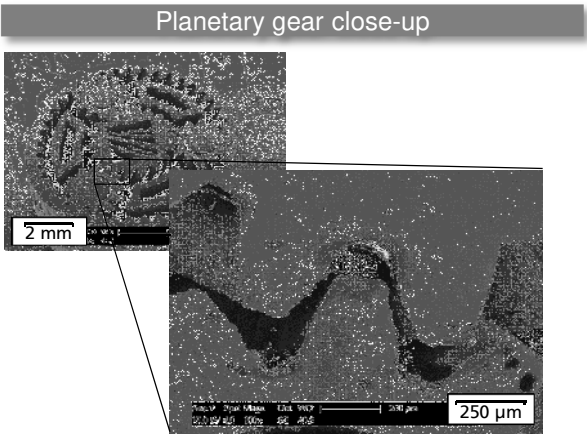


Figure 7: SEM images of the bottom of the helical planetary gear.

As can be seen, the achievable tolerances are sufficient to produce planetary gears with a total diameter of 6 mm.

The process' high detail resolution also enables the production of small joints in addition to planetary gears.

Figure 8 shows an octopus demonstrator. The tentacles of the octopus consist of several articulated joints. The entire octopus was built in one piece. The tentacles can be freely moved after the object is separated from the substrate.



Figure 8: Octopus demonstrator with tentacles consisting of several articulated joints. Made from 316L.

Figure 9 shows that it is also possible to produce very complex and individualized gold jewelry with μ -PBF in one process step.



Figure 9: Realizer SLM-50 substrate with jewelry made of gold.

This application is particularly interesting since the jewelry industry is so large. Furthermore, the possibility of miniaturization represents a promising approach for employing μ -PBF in this and other industrial sectors.

CONCLUSION

At Fraunhofer ILT the following results were achieved with the μ -PBF approach developed here:

- Various fine-grained powder materials can be processed into dense ($\rho_{\text{rel}} \geq 99.5\%$) components with a high degree of complexity.
- Structures with minimal structure widths of down to $32\ \mu\text{m}$ can be built.
- A surface roughness of $S_a = 1.3\ \mu\text{m}$ was achieved without further postprocessing.
- Due to the low surface roughness and the high detail resolution, functional parts such as planetary gears or articulated joints can be realized.

The demonstrators show the great potential of the μ -PBF technology. The μ -PBF process can be used to produce components for:

- medical applications (e.g., minimally invasive surgical instruments),
- micro mechanical applications (e.g., small gears or tools) and
- complex and customized jewelry as shown in Figure 9.

OUTLOOK

Currently, Fraunhofer ILT is continuing research into μ -PBF. Subject of further research activities are:

- processing of other materials such as tungsten, copper and precious metals;
- further reduction of surface roughness and increase of detail resolution; and
- increase in cost efficiency by increasing the μ -PBF process speed.

Therefore, it is planned to develop a new, powder-efficient μ -PBF machine concept that yields higher build rates and unprecedented detail resolution. In addition, possible postprocessing methods will be tested, so that ILT will be able to cover the entire process chain of manufacturing complex micro components.

REFERENCES

- [1] Fischer J, Kniepkamp M, Abele E. *Micro laser melting: Analysis of current potentials and restrictions for the additive manufacturing of micro structures*. 25th Solid Freeform Fabrication Symp. 2014.
- [2] Abele E, Kniepkamp M. *Analysis and optimisation of vertical surface roughness in micro selective laser melting*. Surf. Topogr.: Metrol. Prop. 3. 2015.
- [3] Ebert R, Streek A, Ullmann F et al. *3D Mikrodruck von Metallen – Stand und Perspektiven*: conference proceedings 2. Mitteldeutsches Forum; 3D Druck in der Anwendung. Leipzig: 2015.
- [4] Streek A, Regenfuss P, Exner H. *High Resolution Laser Melting with Brilliant Radiation*. Proceedings of the Solid Freeform Fabrication Symposium. 2014.
- [5] Streek A, Ebert R, Erler M. *Untersuchungen zum Hochrate-Mikro-SLM*. Proceedings of 9. Mittweidaer Lasertagung 2016.
- [6] Masseling L, Hagedorn Y. *Fabrication of micro structures with NiTi shape memory alloy via μ SLM*. Conference proceedings Direct Digital Manufacturing Conference. Berlin: 2016.
- [7] Santos R. *Additive Fertigung von Mikrostrukturen mit SLM*: annual report, Fraunhofer ILT. Aachen: 2013.
- [8] Poprawe R, Hinke C, Meiners W. *SLM Production Systems. Recent Developments in Process Development, Machine Concepts and Component Design*. Advances in Production Technology. Springer. 2015.
- [9] Realizer GmbH. Realizer kompakt SLM-50; datasheet. <http://www.realizer.com/startseite/support/downloads-slm50-slm100-slm250> (accessed 10.2015).
- [10] MCA. Manual for the laser-converter-tester LCT3001. <http://mcamicro.de/laserdown.html> (accessed 10.2015).
- [11] Langbein S, Czechowicz A. *Konstruktionspraxis Formgedächtnistechnik*. Vieweg. 2013.
- [12] Shishkovsky I, Yadroitsev I, Smurov I. *Direct selective laser melting of nitinol powder*. ScienceDirect, Physics Procedia vol. 39. Elsevier. 2012.

ADAPTED SCAN STRATEGY AND SLICING TOOL FOR IMPROVEMENT OF STRUT PRECISION IN LATTICE STRUCTURES

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INTRODUCTION

Lattice structures manufactured by laser beam melting (LBM) are highly recommended as load bearing parts of lightweight constructions. Besides the lightweight-aspects lattice structures can speed up the LBM manufacturing process and therefore reduce costs. But the lack of reliably predicting their mechanical behavior is still an unsolved barrier for their use in numerous industrial applications. In other applications, performance of parts can be significantly improved by the use of precisely manufactured structures with a predefined surface roughness, e.g. in fluid applications in heat exchangers, mixers and chemical reactors.

The quality features of a lattice structure are: evenness of their struts, the accuracy of the strut diameters, their surface roughness and their mechanical behavior [1]. Their mechanical behavior is significantly more dependent on the geometrical features than for objects out of solid material [2, 3]. Therefore achieving a precise and even geometry of the struts, compliant with the predefined geometric specifications, is mandatory for gaining the desired mechanical behavior and also for enabling sufficient prediction of the strut's mechanical behavior by use of FEM-simulation [4].

An important factor for the gained quality of the struts is the slicing process. Currently used slicers are optimized for solid objects. They use a contour-hatch (CH) scan strategy where the contour line of an area to be filled with material is scanned and the filling area is scanned by the laser in a meandering pattern. But these slicers tend to produce failures if it comes to thin walled and fine structures. As shown in FIGURE 1 four main types of failures can be distinguished. Especially the inconsistent energy input by insuffi-

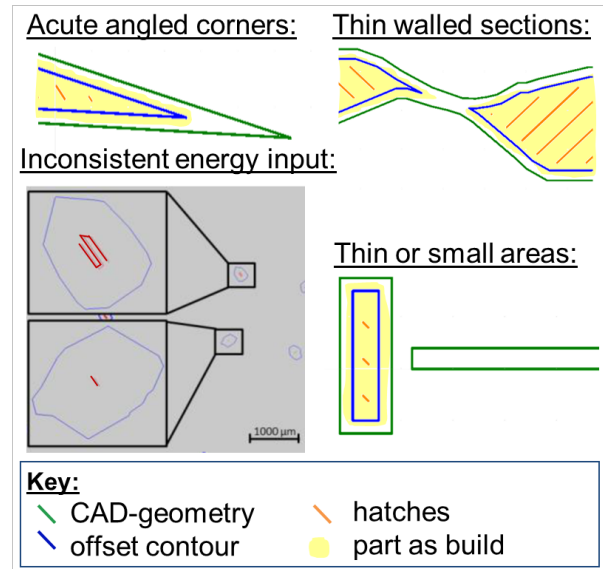


FIGURE 1. Four common types of failures if fine structures are sliced with standard slicing algorithms.

cient scan hatches is a reason for inhomogeneous strut diameters in lattice structures [3].

Finer struts and more homogeneous strut diameters can be achieved if the point (P) scan strategy is used for lattice structures [5]. Using P scan strategy every strut is exposed by a single Laser-Point resulting in a dot-shaped meltpool (cf. FIGURE 2, a)).

MODELLING AND LATTICE CREATION

As P scan strategy is not accessible on most commercially available LBM machines, in this work a slicing algorithm for generating a pseudo P scan strategy, that combines advantages of CH- and P scan strategy [3] is used.

In pseudo P scan strategy, the points of intersection between slicing plane and struts are represented by single short scan vectors as can be

seen in FIGURE 2. a) shows P scan strategy, the others refer to pseudo P scan strategy, in b) the scan vector is oriented in direction of the strut's tilt direction, in c) two crossed scan vectors are used to represent the strut and in d) the scan vector is oriented vertically to the tilted strut. The strut diameter can be defined by the length of the scan vectors and the used laser parameters. A database with the relation between parameters and resulting strut diameter is established.

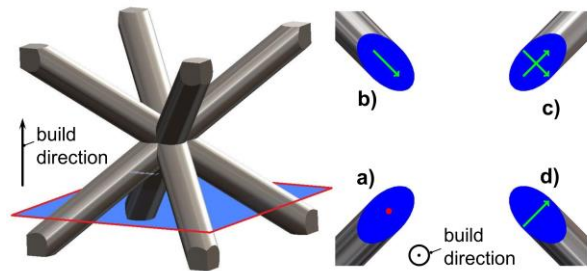


FIGURE 2. Different orientations of scan vectors in P and pseudo P scan strategy.

Whereas the laser beam has to be guided in a small circle and a meandering shape for exposure of every single strut in CH scan strategy, using pseudo P scan strategy in one slice only one scan vector per strut is needed. This results in a significant increase of manufacturing speed. The arrangement of scan vectors in an exemplary slicing plane can be seen in FIGURE 3. The workflow from part design over lattice integration to slicing is fully integrated in a CAD-environment.

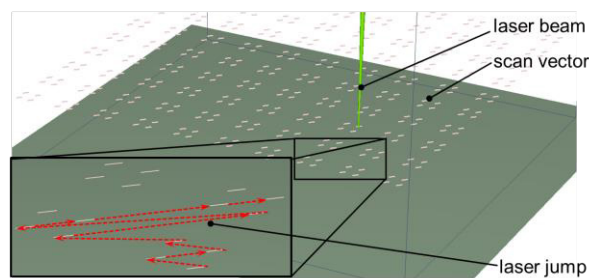


FIGURE 3. Arrangement and order of scan vectors in the slicing plane using pseudo P scan strategy.

TESTS ON GEOMETRICAL INTEGRITY AND MECHANICAL PROPERTIES

The geometrical accuracy is verified by building lattice specimens varying the length of the scan vectors and the process parameters. Resulting strut diameters are measured with digital optical

microscopy. A qualitative assessment of the strut's surface quality is done by manual classification into four quality classes (cf. FIGURE 4).

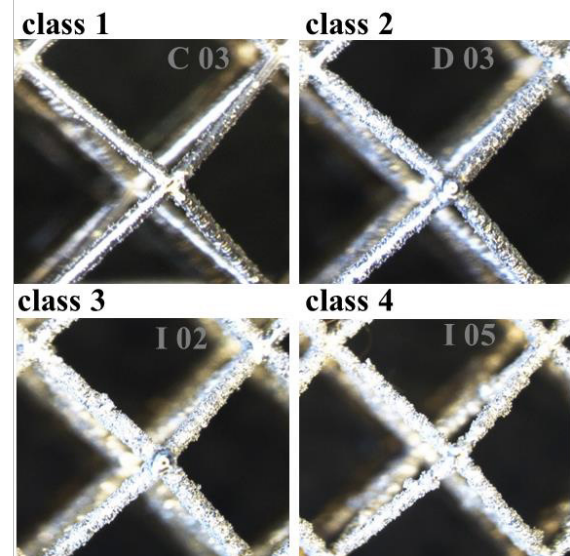


FIGURE 4. Exemplary lattice specimens for the four quality classes of the strut's surface roughness.

The surface quality of selected specimens is additionally determined qualitatively by SEM analysis. Furthermore build speeds of different chronological orders of the scan vectors are evaluated using video captures of the build process.

Compression tests according to German standard DIN 50314 ("Compression test of metallic cellular materials") [6] are carried out for determination of mechanical characteristics. The experimental setup is shown in FIGURE 5. The specimens used have a cubic shape with a base area of 10 x 10 unit cells (cell type: bcc) and a height of 15 unit cells. Edge length of the unit cell is varied from 1 mm to 3 mm. All specimens are made of 6Al 4V Titanium-alloy.

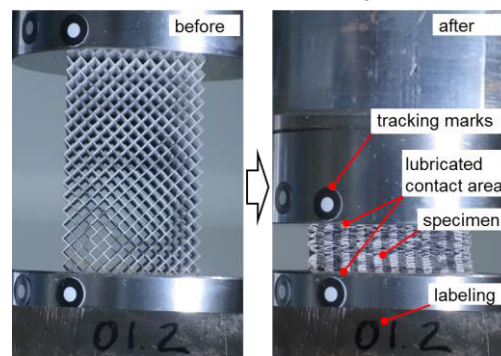


FIGURE 5. Experimental setup of the compression tests.

RESULTS AND DISCUSSION

The pseudo P scan strategy shows up different advantages concerning the strut quality. Additionally it could be shown that it is possible to adjust the surface roughness of the struts by varying the laser parameters. It could also be shown that the pseudo P scan strategy significantly speeds up the manufacturing of lattice structures compared to the CH scan strategy. The results of the mechanical properties determination indicate that pseudo P scan strategy can be a valid alternative to CH scan strategy, especially for strut diameters below 400 μm .

Strut Diameter and Quality

As shown in FIGURE 6, compared to lattice creation using CH scan strategy with a standard slicer, the lattices manufactured with the pseudo P scan strategy can exhibit significantly thinner and more even struts, using the same process parameters.

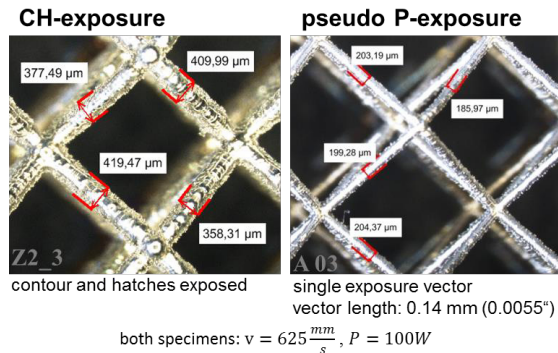


FIGURE 6. Digital optical microscope images of lattice structures manufactured with different scan strategies

Under use of SEM the variation of the diameter within one single strut between CH and pseudo P scan strategy is highly visible (cf. FIGURE 7).

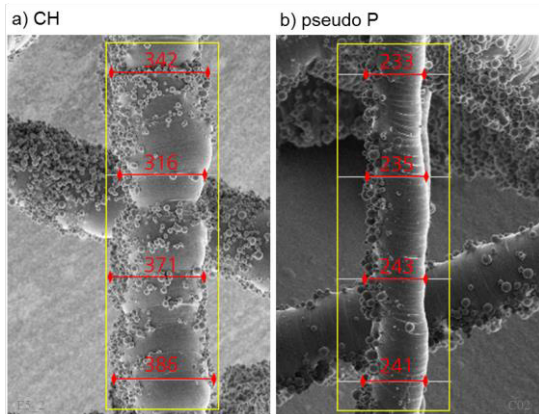


FIGURE 7. Comparison of strut quality between specimens with same process parameters on the basis of SEM images.
a) CH scan strategy with standard slicer,
b) pseudo P scan strategy.

Surface Roughness

Energy input and therefore strut diameter can be adjusted by choosing an appropriate scan vector length and then be fine tuned by selecting a suitable set of scan parameters. As shown in FIGURE 8, the surface roughness can be varied by this combination within boundaries defined by the manufacturing method. Even smoother surfaces are achievable if appropriate scan vectors are chosen. FIGURE 8a) shows the surface quality classes for a single vector exposure (cf. FIGURE 2d)), FIGURE 8b) shows the surface quality classes for a crossed vector exposure (cf. FIGURE 2c)). It shows up, that the scan vector length needed to achieve the minimal surface roughness (dotted lines) increases with higher laser powers. It can also be seen that smoother surfaces can be achieved using crossed vector exposure especially for higher laser powers.

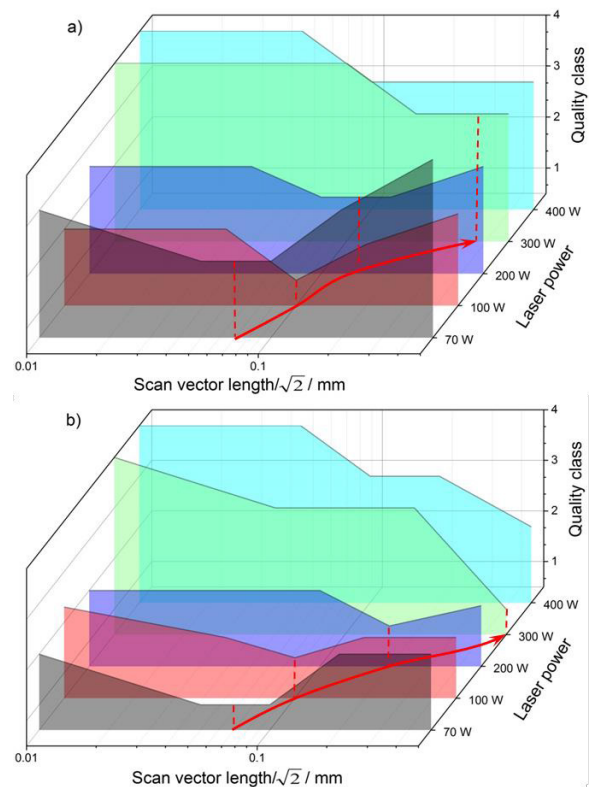


FIGURE 8. Dependencies between scan vector length, laser power and surface quality class for pseudo P single scan vector exposed lattice specimens.

Mechanical Properties

The analysis of the microsection suggests that no significant differences between the mechanical characteristics of CH exposed and pseudo P exposed lattice structures are to be expected.

Both show up a similar form of α' -martensitic micro structure, as can be seen in FIGURE 9. This assumption could be confirmed in by the following compression tests.

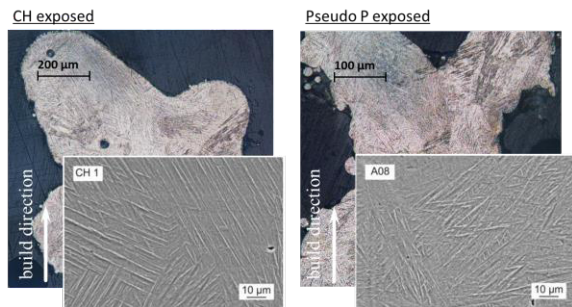


FIGURE 9. Comparing SEM Images of the micro structure of CH exposed specimens and Pseudo P exposed specimens.

In the compression Tests a high reproducibility of plateau stresses between identical specimens could be achieved: the differences in plateau stresses of pairs of two identically manufactured specimens were calculated. The mean of these differences is over all specimens only 0.02 MPa with a standard deviation of 0.17 MPa.

The plateau stress is used here as an indicator for the strength of a lattice structure. The data points obtained by pseudo P scan strategy predominantly form a graph, as can be seen in FIGURE 10. It could be shown that it is possible to cover at least the section between 0.5 % and 20 % relative density by the use of pseudo P scan strategy. This range can especially be achieved by variation of the strut length.

Another outcome is that the results of the compression tests carried out here are in a good accordance with the results of Hasan [6].

Furthermore the plateau stress referred to the relative density of specimens manufactured with CH scan strategy do not significantly differ from those of pseudo P exposed ones. Thus, from the mechanical view it is not a disadvantage to use the faster pseudo P instead of CH scan strategy. Additionally the pseudo P scan strategy allows to produce lattice structures with thinner struts than it is possible using CH scan strategy. This expands the graph especially in the field of low relative densities. Due to the restrictions of the production process pseudo P scan strategy is especially suitable for strut diameters under 400 μm , thicker struts can either be produced using pseudo P or CH scan strategy.

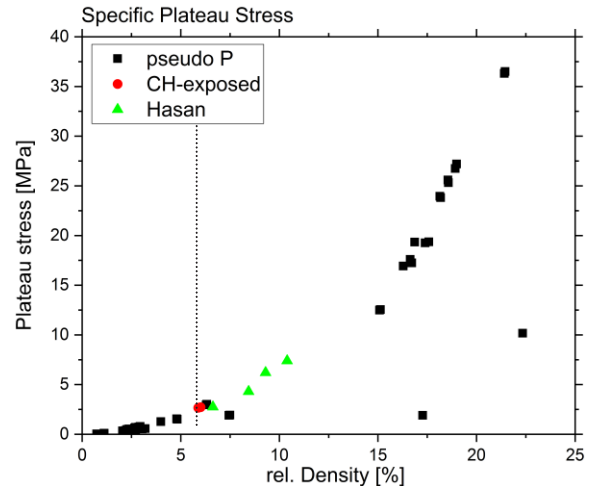


FIGURE 10. Determined plateau stress for different specimens referring to their relative density with comparison to the results of Hasan [7].

Concerning the Young's Modulus, a wide range of different Moduli can be covered by pseudo P scan strategy. The data points for the Young's Modulus of different specimens exhibit an exponential correlation between the relative density and the Young's Modulus (cf. FIGURE 11). The results of Hasan [6] do as well match the data of the pseudo P scan strategy. The strut length again shows the biggest influence on the Young's Modulus, the Moduli determined for the CH exposed specimens do fit well into the graph formed by the pseudo P exposed specimens. However, it is likely that the manufacturing parameters (strut length and laser parameters) can be interpolated for missing values of Young's Modulus.

Especially the possibility to manufacture lattice structures which exhibit Young's Moduli in the magnitude of those of the human bone (apx. 1 GPa) and the probability of a tailored Young's Modulus recommends this type of lattice structures for the use in the field of bone implants.

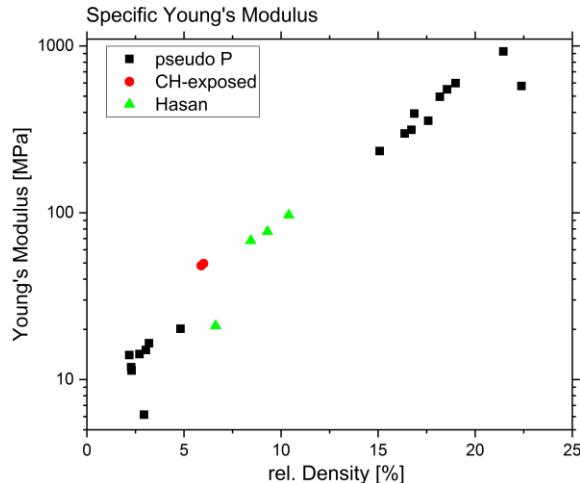


FIGURE 11. Linear relation between relative density and Young's Modulus on a logarithmic scale.

FUTURE WORKS

Besides the stress strain curves as a result of the compression tests, the deformation behavior could be analyzed more precisely by use of a video capture and the automated recognition and tracking of the lattice's intersections. This could be used to develop a suitable simulation model for the deformation behavior of lattice structures.

Furthermore the struts manufactured by pseudo P scan strategy currently exhibit a tapering at their ends. It is assumed that this is due to a low energy input, as heat dissipation is stronger at the intersections of the lattice structure than within the struts. This could be solved by exposing the intersections with higher laser power and longer scan vectors.

Within the scope of this work only the bcc-cell type has been considered, as the main objective was to evaluate the influence of manufacturing parameters on the strut quality using pseudo P scan strategy. But bcc-cell type is by far not suitable to withstand compression forces in one of its principal directions. Especially for the use in lightweight constructions, a high Young's Modulus and a high strength are wanted. So after it could be shown that improving the strut quality is possible, further research could focus on the increase of the Young's Modulus and strength by choice of suitable cell types.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] VDI-Richtlinie VDI 3405 – Part 2, 08.2013: Additive manufacturing processes, rapid manufacturing – beam melting of metallic parts – Qualification, quality assurance and post processing.
- [2] Abele E; Stoffregen H; Klimkeit K; Hoche H; Oechsner M Optimisation of process parameters for lattice structures. In: Rapid Prototyping Journal 21 (1), S. 117–127. (2015)
- [3] Korn H; Koch P; Kordaß R; Schöne C; Müller B; Holtzhausen S; Stelzer R (2018): Influences of Scan Strategy and Exposure Parameters on Diameter and Surface Quality of Struts in Lattice Structures. In: Fraunhofer Generativ (Hg.): DDMC - Direct Digital Manufacturing Conference 2018 Berlin.
- [4] Karamooz Ravari, M R; Kadkhodaei, M (2015): A Computationally Efficient Modeling Approach for Predicting Mechanical Behavior of Cellular Lattice Structures. In: J. of Materi Eng and Perform 24 (1), S. 245–252. DOI: 10.1007/s11665-014-1281-4.
- [5] Ghose S; Babu S; van Arkel R J; Nai K; Hooper P A; Jeffers J (2017): The influence of laser parameters and scanning strategies on the mechanical properties of a stochastic porous material. In: Materials & Design. DOI: 10.1016/j.matdes.2017.06.041
- [6] DIN 50134:2008-10: Prüfung von metallischen Werkstoffen – Druckversuch an metallischen zellularen Werkstoffen.
- [7] Hasan R (2013): Progressive Collapse of Titanium Alloy Micro-Lattice Structures Manufactured Using Selective Laser Melting. Dissertationsschrift. University of Liverpool, Liverpool (Großbritannien).

GEOMETRIC AND FEATURE SIZE DESIGN EFFECT ON VAT PHOTOPOLYMERIZATION MICRO ADDITIVELY MANUFACTURED SURFACE FEATURES

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INTRODUCTION

Additive Manufacturing (AM) is a group of processes that are characterized by manufacturing a 3D model by adding material in layers. AM technologies allow fabricating directly from a 3D CAD model, without the need of process planning.

Latest advances in AM have been focused in improving its accuracy, introducing AM in the micro manufacturing area (μ AM) [1]. Inside AM, the Vat Photopolymerization (VP) methods are characterized by curing or hardening a liquid photopolymer, layer by layer, by means of an Ultraviolet (UV) light. Depending on the precision and resolution with which they project the UV light they can be applied in normal-size manufacturing as well as in micro-manufacturing. Specifically, when the layer is cured by mask projection of the UV light, the technology is called Digital Light Processing. In contrast to other VP methods, like Stereolithography, that solidify the resin in a point-by-point style, DLP cures a layer of resin at a time in one projection.

In order to expand the applications for AM it is significant to achieve predictable and repeatable shapes of the features, i.e. how accurate the AM machine has the ability to print different feature geometries. For example, the dimensional and geometrical accuracy for fused deposition modeling, laser sintering and laser melting methods have been evaluated in previous studies [2].

At the Technical University of Denmark (DTU), a DLP proprietary machine has been developed, built and validated [3]. This machine is able to print micro-scale features. This study analyzes the capability of this DLP machine in terms of geometry and smallest printing feature size when manufacturing micro-features with

different geometries, while keeping the machine settings constant.

MATERIALS

In this section, the AM DLP machine that has been characterized is presented in the first subsection. The second subsection describes the test parts that have been designed to perform the study.

DLP Machine

The AM method under study employs a DLP based video projector that contains a micro-opto-electro-mechanical mirror array, a Digital Micromirror Device (DMD), to modulate a collimated UV light source, which is subsequently focused to an imaging plane placed on the bottom surface of a transparent vat. In Figure 1 the schematic of the process is shown.

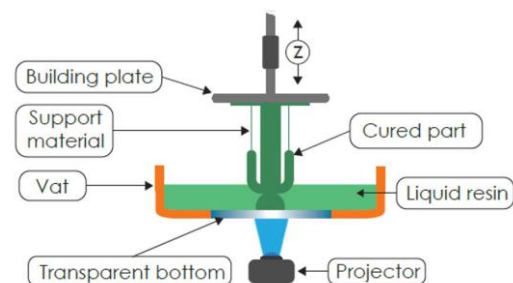


FIGURE 1. Schematic representation of the DLP vat polymerization process, in a bottom-up configuration.

The resolution of the build-stage in the vertical direction is $0.4\ \mu\text{m}$. The projection mask pixel spacing is $7.6\ \mu\text{m}$ in the image plane, which dictate that any feature will be resolved to a $7.6\ \mu\text{m}$ pixel grid in the image plane and with a height corresponding to the layer height of the

machine. The experimental machine-tool has been engineered, built and validated at the AM Laboratory of the Technical University of Denmark and it was tested by printing different micro features [4] [5]. Figure 2 shows a picture of the proprietary machine.

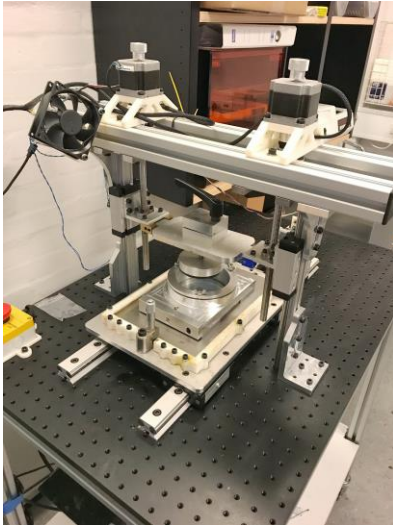


FIGURE 2. Proprietary Digital Light Processing Machine.

The selected printing parameters used in this work are presented in Table 1.

TABLE 1. Printing settings

Parameters	Selected Parameters
Layer thickness/ μm	25
Exposure time/s	3.5
Light intensity	230
Resin	FTD red resin

After the machine has finished printing the part, it is necessary to remove it from the vat and clean the liquid resin that remains on the sample. The isopropyl alcohol (IPA) was used for the cleaning process. Once the part was clean (without any leftover resin), it was dried with pressurized air. Afterwards, to complete the curing of the photopolymer, the part was placed in a UV oven for 80 minutes.

Test Part

The performance and capability study of the machine can be done by producing, measuring and characterizing test parts [6]. In this work, the performance and capability of the machine when printing two different geometries in different

sizes have been analyzed: hollow box and hollow cylinder. For this purpose, two test parts have been designed, each one containing one type of geometry.

In each test part, the geometries are positioned in a matrix of 6×20 on a base of $12 \times 12 \times 2 \text{ mm}^3$, as shown in Figure 3. They are separated a distance of $250 \mu\text{m}$ between each other with a 3:4 aspect ratio for the lateral size. In the rows, the features are ordered decreasingly from top (1.5 mm in diameter/width) to bottom ($6 \mu\text{m}$ in diameter/width). The six rows are equivalent, in order to study the repeatability in one printout. The nominal height of all the geometries is $500 \mu\text{m}$. Each test part was printed five times in five different days, in order to study the reproducibility of the machine. The printing range of the machine allows printing just one test part at a time. The printing time of each of the test parts is about thirty minutes.

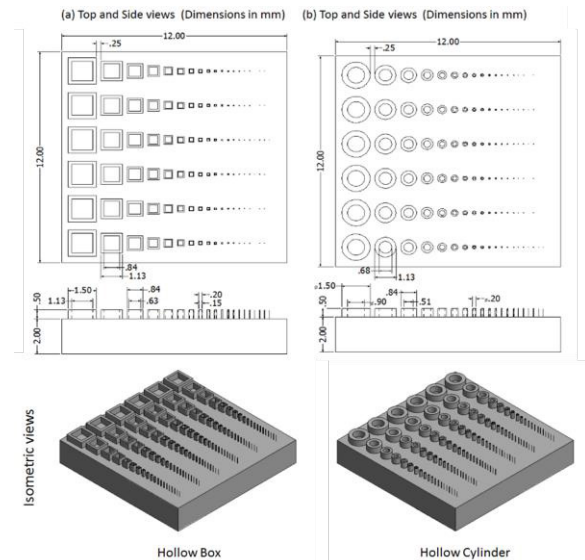


FIGURE 3. Top and side views of (a) hollow box, (b) hollow cylinder and isometric views

MEASUREMENTS AND DATA PROCESSING

The measurements have been performed by means of a focus variation Alicona Infinite Focus microscope. The $5\times$ magnification lens were used for visual inspection of the features. The $10\times$ magnification lens were used to capture the data of the geometries to be measured. The $10\times$ magnification lens have a pixel width of $883 \text{ nm} \times 883 \text{ nm}$. The vertical resolution of the measurements is 200 nm and the lateral resolution is $3 \mu\text{m}$.

The features that have been checked by visual inspection are the smallest features having the right shape and the smallest printed features

regardless of the shape. The boxes are considered to have the right shape when, despite of the rounded edges, orthogonal straight lines can be observed. Similarly, the cylinders are considered to have the right shape, when their roundness is higher than 0.8.

The features having dimensions 840 μm of diameter/width (third column of the matrix) were evaluated in terms of form (circularity and squareness). To performed the measurements, the top surface of the feature was capture with the microscope and a set of point cloud data was obtained. Then, this data needs to be post-processed. In this study, the Image Metrology SPIP© software [7] was used for this purpose. Firstly, the surface was leveled to be in the XY-plane. In the hollow boxes, the orthogonality of the outer surfaces was assessed by measuring the angle of each edge separately. The lateral surfaces were approximated to a straight line, performing a best-fit. The circularity of the outer surface of the hollow cylinders is measured by a function of SPIP, according to ISO [8]. The circularity is evaluated from 0 to 1, as the degree to which the particle is similar to a perfect circle (1), considering the smoothness of the perimeter.

$$C = \sqrt{\frac{4\pi A}{P^2}} \quad (1)$$

Then, considering Equation 1, circularity is a measurement of both the particle form and roughness independently of its size [9].

RESULTS

In this sections the experimental results that have been obtain for the hollow boxes and the hollow cylinders are presented. Figure 4 shows the image of the printed samples with two different geometries.

For each case, the repeatability and reproducibility when manufacturing a geometry in terms of form (squareness and circularity) have been analyzed. Each test part, in each column, has the same feature repeated 6 times (one batch). This was used for the assessment of the repeatability. In addition, each test part was manufactured 6 times, in order to assess the reproducibility as well.

In both cases, the features that have been analyzed are the ones in the third column (840 μm of diameter/width). This are the biggest features that could be measured using the 10 $\times$ magnification lens, in just one image, without stitching. Nevertheless, it was observed by

visual inspection, that bigger features presented a similar trend.

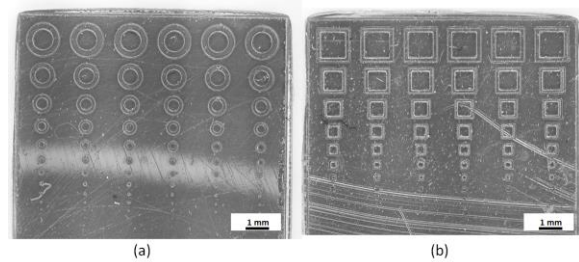


FIGURE 4 printed sample (a) cylinder (b) box

Hollow boxes

In the hollow boxes test part, the smallest printed feature was in the 10th column (360 μm), but it was neither hollow, nor square. The smallest hollow box printed that was actually hollow and square was in the 7th column (630 μm).

The perpendicularity of the hollow boxes was evaluated by measuring the deviations of each of the edges from the right angle. In Figure 5, the average edge angle of each batch has been represented. The error bars, represent the repeatability of each batch, calculated considering a uniform distribution. Considering all the measurements of all the batches, these angles presents an average of 90° 00" with a reproducibility of $\pm 1.55^\circ$.

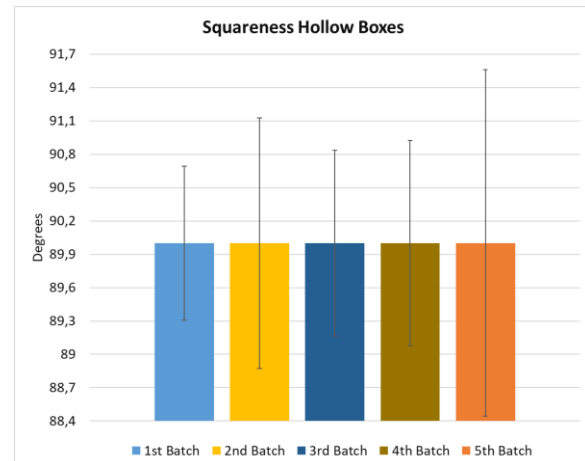


FIGURE 5. Squareness for hollow boxes

Hollow cylinders

Regarding the hollow cylinders test part, the smallest printed feature is in the 13th column (200 μm), but it was neither circular, nor hollow. The smallest hollow cylinder printed that is actually hollow and circular is in the 11th column (360 μm).

Similarly as in the previous subsection, in Figure 6, the average circularity of each batch has been represented. In turn, the error bars represent the repeatability of each batch. Considering all the measurements of all the batches, the circularity presents a mean of 0.908, with a standard deviation of ± 0.037 , considering a uniform distribution.

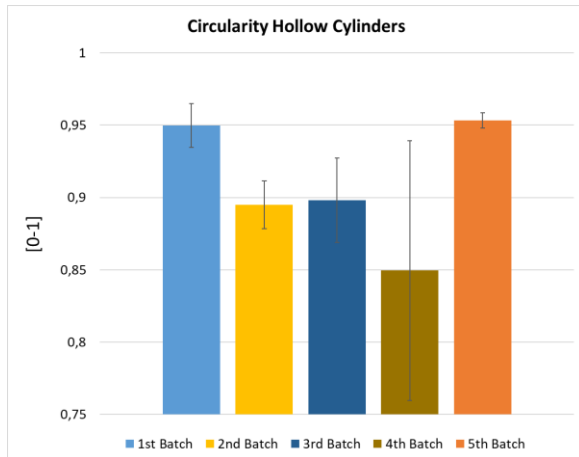


FIGURE 6. Circularity for hollow cylinders

CONCLUSIONS

The limits of a proprietary DLP machine were characterized in terms of form and smallest printed features in different geometries. The influence of different designs with the same geometry was evaluated and the reproducibility of the machine was investigated.

The test part of the hollow cylinders presents the smallest printed feature, having better results than the test part of the hollow boxes. This is due to the fact that printing the sharp edges of the hollow boxes require more precision than printing a rounded shape.

From evaluating the results in terms of squareness obtained for the hollow boxes, it can be deduced that in every batch the average is $90^{\circ} 00''$ because all the sides are straight surfaces that form a parallelogram, even though, the edges are rounded. Nevertheless, the repeatability varies from one batch to the other, which means that the performance of the machine varies in every print. This could be due to the fact that every time the proprietary machine is going to be used, it needs to be calibrated manually. In some cases, this calibration could have been performed more precisely than in others.

The results obtained for the hollow cylinders in terms of circularity are similar. Batches 1, 2, 3 and 5 present a small repeatability, while the repeatability of the batch 4 is more than 3 times higher than the others. This could be due to the same reason previously stated.

Therefore, the calibration of the machine could be standardized in order to improve the repeatability and reproducibility of the results.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA grant agreement no. 609405 (COFUNDPostdocDTU) and the project DPI2015-69403-C3-1-R "MetroSurf". The authors would also like to acknowledge the FPU Program of the Ministry of Education, Culture and Sports of the Spanish Government and the Program Ibercaja-CAI for Research Stays, which sponsored the PhD student L. C. Diaz Perez.

REFERENCES

- [1] Vaezi M, Seitz H, and Yang S. A review on 3D micro-additive manufacturing technologies. *Int. J. Adv. Manuf. Technol.* 2013; 67; 5: 1721–1754.
- [2] Lieneke T, Adam GAO, Leuders S, Knoop F, Josupeit S, Delfs P, et al. Systematical determination of tolerances for additive manufacturing by measuring linear dimensions. 26th Annu. Int. Solid Free. Fabr. Symp. Austin, 2015.
- [3] Jørgensen, AR. Design and development of an improved direct light processing (DLP) platform for precision additive manufacturing. Technical university of Denmark (DTU). 2015.
- [4] Davoudinejad A, Ribo MM, Pedersen DB, Islam A, Tosello G. Direct fabrication of bio-inspired gecko-like geometries with vat polymerization additive manufacturing method. *J Micromechanics Microengineering*. 2018.
- [5] Davoudinejad A, Pedersen DB, Tosello G. Evaluation of polymer micro parts produced by additive manufacturing processes by using vat photopolymerization method. *Jt. Spec. Interes. Gr. Meet. between euspen ASPE Dimens. Accuracy Surf. Finish Addit. Manuf.* 2017.
- [6] Thompson MK and Mischkot M. Design of Test Parts to Characterize Micro Additive Manufacturing Processes. *Procedia CIRP*. 2015; 34; 223–228.

- [7] "SPIP-www.imagemet.com."
- [8] ISO 9276-6:2008 Representation of results of particle size analysis - Part 6: Descriptive and quantitative representation of particle shape and morphology
- [9] Olson E. Particle Shape Factors and Their Use in Image Analysis. Journal of GxP Compliance. 2011; 15; 3: 85-96.

DOSAGE COMPENSATION FOR UNIFORM PRINTING WITH NON-UNIFORM BEAMS IN PROJECTION TWO-PHOTON LITHOGRAPHY

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INTRODUCTION

Two-photon lithography (TPL) is a technique that uses a nonlinear photo-absorption process to polymerize, and, therefore, solidify submicron features within the interior of a liquid photopolymer resist. In TPL, complex three-dimensional (3-D) structures can be additively manufactured by the relative motion between the focal volume of an ultrafast laser beam and the liquid photopolymer resist. TPL was initially researched and developed in the 1990s [1].

TPL has been used to additively manufacture polymer parts with submicron features for microfluidic devices [2], metamaterials [3], photonic applications [4], and bio-cell scaffolds [5]. The relative motion between the laser focus and the resist volume is often realized through serial scanning with 1) an XY motion stage carrying the liquid drop of the resist, 2) a Z-stage carrying an objective lens to focus the laser beam, and 3) a two-axis galvanometric scanner to steer the beam to any point within a pre-determined space in the XY plane. This serial technique limits the writing speed to 0.01 – 0.10 mm³/hr. Such a low printing speed precludes the industrial scale adoption of TPL.

To massively increase the throughput of TPL, we have developed and tested a parallel TPL technique that increases the TPL printing rate by at least 35 times while still guaranteeing submicron feature sizes laterally. In a parallel TPL system, a digital micromirror device (DMD) steers a series of pre-programmed two-dimensional (2-D) patterns to the objective lens. Instead of focusing the laser beam into a single voxel as in serial TPL, here, the entire pattern projected by the DMD is focused on the focal plane of the objective. This polymerizes an entire 2-D layer (with the lateral dimensions proportional to those of the DMD pattern) in the liquid volume of the resist. Three-dimensional structures are formed by switching to the next

desired DMD pattern and moving the Z-stage so that the next layer can be printed on top of a previously-printed layer.

With Gaussian beam profiles that are commonly observed in industrial lasers, there is a need for beam shaping so that the beam used for parallel TPL has a uniform flat-top intensity profile. This ensures the uniformity of polymerized resist layers over the entire projected area. Beam shaping using optics have been widely utilized to obtain a flat-top profile [6]. A key issue with beam shaping optics is that the flat-top intensity profile is not a free-space mode. The flat-top intensity profile of the beam can be maintained only for a short propagation distance within tens to a few hundreds of millimeters. At a larger propagation distance, the flat-top intensity profile converges to a non-uniform Airy pattern. This path-length limitation of beam shaping imposes a constraint on the performance of the system. In addition, the use of diffractive beam shaping optics in parallel TPL requires additional beam expanders and reducers to match the size of the beam to that of the aperture of the beam shaper and the DMD. As ultrashort pulses are highly stretched and dispersed through optical media [7], additional optics in the beam path adversely affect the intensity of the projected pattern. Thus, there is a need to develop an alternative to conventional beam shapers for parallel TPL. Here, we have developed and demonstrated a dosage compensation technique to ensure uniform printing with a non-uniform beam intensity profile. We achieve this by controlling the duration of exposure of the pixel points on the DMD to compensate for the non-uniform profile of the laser intensity.

PROJECTION TWO-PHOTON LITHOGRAPHY

Parallel two-photon lithography with the projection of thin light sheets and polymerization of an entire resist layer has not been realized and reported in the literature. The challenges to

accomplish this include 1) the laser power loss after the DMD, 2) the dispersion and stretching of the broad-band laser beam after reflection from the DMD, and 3) the dosage control to enable polymerization of the resist material.

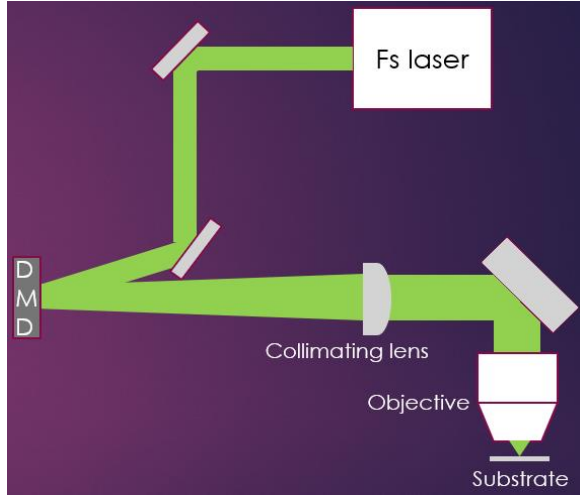


FIGURE 1. Schematic of the TPL system.

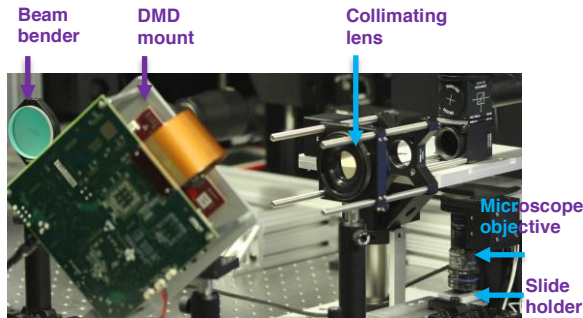


FIGURE 2. A photograph of the projection optics.

Our newly developed parallel TPL system includes 1) a femtosecond laser with 800-nm central wavelength, 35-fs pulse width, 1-kHz repetition rate, and 7-mJ maximum pulse energy, 2) a DMD with 1920 pixels $\times$ 1080 pixels, and 7.56- μm pitch [8], 3) a collimating lens, 4) a microscope objective to focus the laser beam, 5) a Z-stage to position the objective, and 6) an XY-stage to position the substrate carrying a drop of liquid photoresist. The polymerizable photoresist used herein is an acrylate-based resin with a photoinitiator and a monomer. Fig. 1 shows the system's schematic representation. Fig. 2 is a photograph of the projection optics.

DOSAGE COMPENSATION

As a first-approximation, here we have used the simplistic threshold model presented by Mueller *et al.* [9] to formulate our dosage compensation technique. According to this threshold model, the different exposure conditions in TPL are regarded as similar if the time-averaged number of radicals generated through photo-exposure is the same. Accordingly, the dosage D depends on the process parameters as:

$$D = \tau R E_p^N. \quad (\text{Eq. 1})$$

Here, τ , R , E_p and N are, respectively, the exposure time, repetition rate of the pulsed laser, laser pulse energy, and the nonlinearity of the absorption process. For a two-photon absorption process, the nonlinearity parameter N is equal to 2.

In this work, the repetition rate of the pulsed laser is 1 kHz. The total pulse energy of the beam incident to the DMD is fixed for each experiment. However, the laser power intensity is spatially distributed as a Gaussian profile. To make the exposure dose D as uniform as possible over the entire area projected by the DMD, one can vary the average exposure time τ at each micromirror to compensate for the spatial variation of the pulse energy E_p . A known spatial distribution of the pulse energy E_p can be used to calculate the required exposure time τ at each individual micromirror of the DMD.

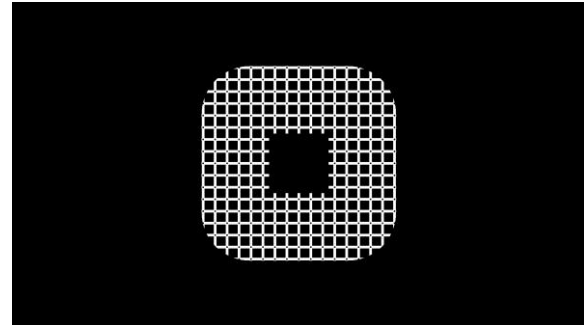
A DMD image used in this work is a bitmap of 1920 pixels $\times$ 1080 pixels. Each bitmap point in the DMD image represents a micromirror that can be actuated and tilted by 12° (ON) and -12° (OFF). A bitmap point of 1, which is visualized as the white color, or full brightness, indicates that the associated micromirror steers the corresponding part of the beam to the objective lens for a predetermined duration of exposure. A point of 0, visualized as black (the background color of the bitmap image), indicates that the corresponding part of the laser beam is steered away from the objective lens for the entire duration of exposure. Each bitmap image loaded into and projected by the DMD, therefore, represents a slice of the 3-D structure to be printed. A bitmap point of 1, therefore, corresponds to a point in the volume of the desired part to be printed, and a point of 0 corresponds to a location where polymerization is not desired.

With a maximum bit depth of 8, a bitmap pixel brightness can be programmed to have 256 brightness levels between 0 and 1. The DMD mirrors continuously flip between the ON position (12° with respect to the normal direction of the DMD's nominal surface) and the OFF position (-12°) at a predetermined frequency. The duty cycle at a pixel, which is the fraction of the total duration of exposure over which a pixel stays ON, is set by the brightness level of the associated bitmap point. This in turn determines the duration of exposure at each pixel.

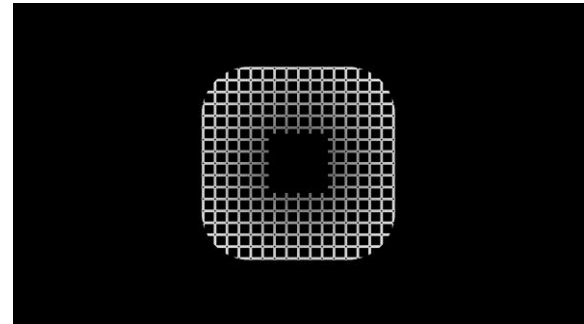
In a certain projection shot with the total exposure time of T (the theoretically maximum duration that a mirror is set to stay at the ON position), with the duty cycle of β set by the bitmap point's brightness for a micromirror, the amount of time this mirror stays at the ON position is βT . The switching time between ON and OFF is considered negligible. With n being the bit-depth number, β can have 2^n different values between 0 and 1. However, due to the constraints of the DMD hardware and controller, the minimum possible exposure T increases with an increase in n . With the bit depth of 8, the maximum pattern-switching rate is 247 Hz and the minimum exposure possible is 4.046 ms [8].

As a demonstration of the dosage compensation method presented in this paper, we have compensated for the Gaussian profile of the incident laser through a grayscale DMD image shown in Figure 3. A fractional bitmap grayscale brightness generates a net printing dosage that is a fraction of the dosage for the full duration of exposure. As an example, a brightness of 0.3 exposes the resist material for a duration of 0.3 times that of the full brightness.

Due to the 1-kHz repetition rate of the laser, the theoretical exposure levels across different pixels can vary by increments of no less than 1 ms. Thus, the compensation method presented herein works best when the number of pulses for the total exposure is equal to or higher than the number of bitmap brightness levels for a given bit depth. For instance, a DMD exposure time of 8 ms or longer should be set for a bit depth of 3 with 8 bitmap brightness levels.



(a)



(b)

FIGURE 3. A non-compensated bitmap image (a), and a Gaussian compensated one (b).

RESULTS AND DISCUSSIONS

Log-pile structures were printed to demonstrate the improvement of the uniformity of the structure with the dosage-compensated beam using computed DMD bitmaps. Figures 4 (a–d) show the effect of this dosage compensation method. The part shown in Figure 4(a) was printed without any dosage compensation. The parts shown in Figures 4(b, c) were printed with the computed bitmap images for the compensation. With a more tightly-controlled compensation of the Gaussian power-intensity profile, structures as shown in Figure 4(d) were printed. Figure 5 is an image of an array of tall pillars printed using the dosage compensation presented herein. This demonstrates that the computed bitmaps can be used to overcome the path-length limitations of the conventional beam shapers. In addition, particularly for parallel TPL, the dosage compensation method presented in this paper minimizes the issues arising from the beam-size incompatibility and pulse stretching in conventional beam shapers.

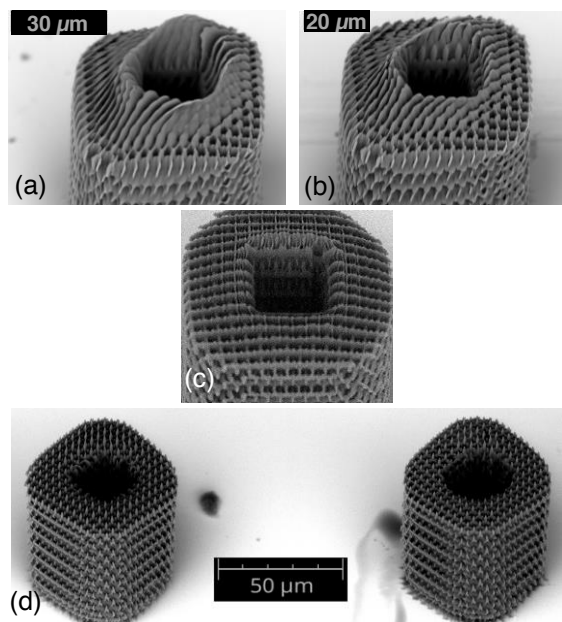


FIGURE 4. Log piles printed (a) without compensation, and (b, c, d) with computed DMD bitmap images to compensate for the Gaussian beam profile.

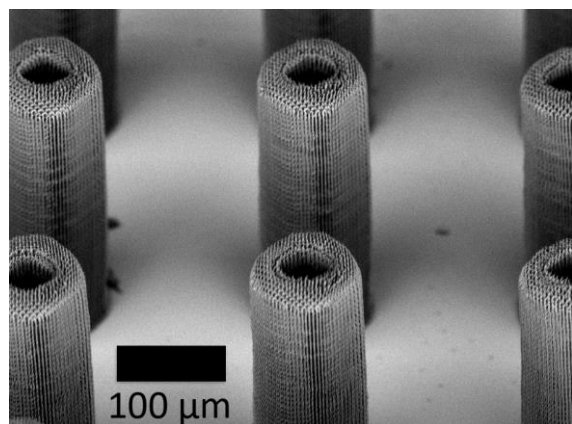


FIGURE 5. An array of pillars printed by parallel TPL using the computed DMD bitmaps to compensate for the Gaussian profile of the femtosecond laser beam.

CONCLUSIONS

In summary, we have demonstrated a dosage compensation method for projection two-photon lithography that enables the generation of uniform 3-D structures with non-uniform beams. This compensates for the non-uniformity of the laser intensity by introducing non-uniformities in the duration of exposure to generate a net uniform dosage throughout the entire field of projection. Our method eliminates the need for

additional beam shaping optics, thereby simplifying the overall optical design of the system. With the calibration of the beam intensity profile, this method can be used to compensate for the non-uniformity of not only Gaussian beams but also any other arbitrarily shaped beams.

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REFERENCES

- [1] Maruo S, Nakamura O, Kawata S. Three-Dimensional Microfabrication with Two-Photon-Absorbed Photopolymerization. *Optics Letters*. 1997; 22(2): 132-134.
- [2] Maruo S, Inoue H. Optically Driven Micropump Produced by Three-Dimensional Two-Photon Microfabrication. *Applied Physics Letters*. 2006; 89(14): 144101.
- [3] Meza L R, Das S, Greer J R. Strong, Lightweight, and Recoverable Three-Dimensional Ceramic Nanolattices. *Science*. 2014; 345(6202): 1322-1326.
- [4] Freymann G v, Ledermann A, Thiel M, Staude I, Essig S, Busch K, Wegener M. Three-Dimensional Nanostructures for Photonics. *Advanced Functional Materials*. 2010; 20(7): 1038-1052.
- [5] Ovsianikov A, Gruene M, Pflaum M, Koch L, Maiorana F, Wilhelmi M, Haverich A, Chichkov B. Laser Printing of Cells into 3D Scaffolds. *Biofabrication*. 2010; 2: 014104.
- [6] Shealy D L, Hoffnagle J A. Laser Beam Shaping Profiles and Propagation. *Applied Optics*. 2006; 45(21): 5118-5131.
- [7] Bor Z. Distortion of Femtosecond Laser Pulses in Lenses and Lens Systems. *Journal of Modern Optics*. 1988; 35(12): 1907-1918.
- [8] Texas Instruments. DLP6500 0.65 1080p MVSP Type A DMD. Oct. 2016.
- [9] Mueller J B, Fischer J, Wegener M. Chapter 3 - Reaction Mechanisms and In Situ Process Diagnostics. In *Micro and Nano Technologies, Three-Dimensional Microfabrication Using Two-photon Polymerization*. William Andrew Publishing. New York: 2016.

CHARACTERISATION OF THE INFLUENCE OF THE COLOUR IN RESIN FOR MICRO PARTS PRODUCTION BY PHOTOPOLYMERISATION BASED ADDITIVE MANUFACTURING SYSTEM

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INTRODUCTION

Colour is one of the most important features which stimulates the perception and functionality of products as it provides the desired appearance and surface finish. It can be applied in polymer processing techniques, which eliminates the painting step, being an advantage over metal, ceramics, wood or glass parts manufacturing. The influence of the pigmentation has been extensively studied in thermoplastics processing techniques, indicating the change of mechanical characteristics and dimensional stability as the most prominent effects [7]. In photopolymerisation-based systems, incorporating pigmentation in the matrix can influence the processing parameters, post-treatment effects and properties of the final product. This is due to the absorption of the incident light by the pigments. Colour has been found to be one of the main determinants of the level of light intensity utilised to cure a coating of set thickness [2]. Based on the previous research the polymerisation efficiency is the highest for unpigmented resins and the lowest for white material, placing black, blue, red and green in the middle [5]. The advancements in photopolymerisation-based manufacturing techniques and materials, dictates further study the issue of light absorption and its influence on the geometry of the resulting features.

The current research investigates the impact of the pigmentation on photopolymers in the curing process, using UV light mask projection method, for micro features reproduction. The critical concern in this analysis is the stability of the resins towards UV light, subjected to varying process parameters in order to determine the minimum achievable layer thickness and optimum UV light intensity for fast, efficient and accurate production of miniaturised parts. The main outcome of this study is creation of a guideline for micro-features manufacturing.

METHODS

All of the experiments took place at Department of Mechanical Engineering, Technical University of Denmark.

Test artefact

A test part with various geometries was designed. The features chosen for the measurements were pillars, grooves, spheres, overhang and angles [6], placed on the base with dimensions of 10 mm x 5 mm x 1 mm. To allow the visibility through the grooves, two pillars were added in the bottom of the part (Figure 1).

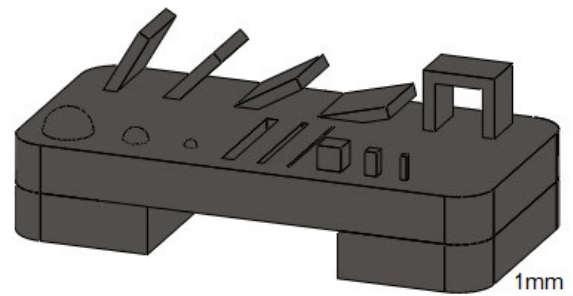


Figure 1: Isometric view of the part selected for the experiments.

AM platform

A UV light mask projection based vat-photopolymerisation platform, with a bottom-up setup was used for the experiment (Figure 2). The system was fully designed and developed at Department of Mechanical Engineering, Technical University of Denmark (Figure 3) and it can reach the level of vertical accuracy down to 1 μm . The machine uses a Visitech LUXBEAM[®] LRS-WQ-HY projector with an integrated light engine DLP9000 DMD with a resolution of 2560x1600p and 7.54 μm pixel pitch.

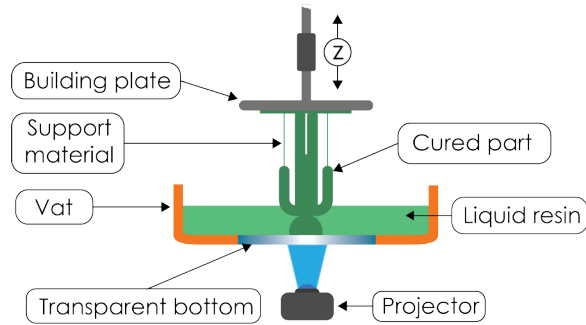


Figure 2: The principle of the UV light mask projection-based vat-photopolymerisation technique [4].

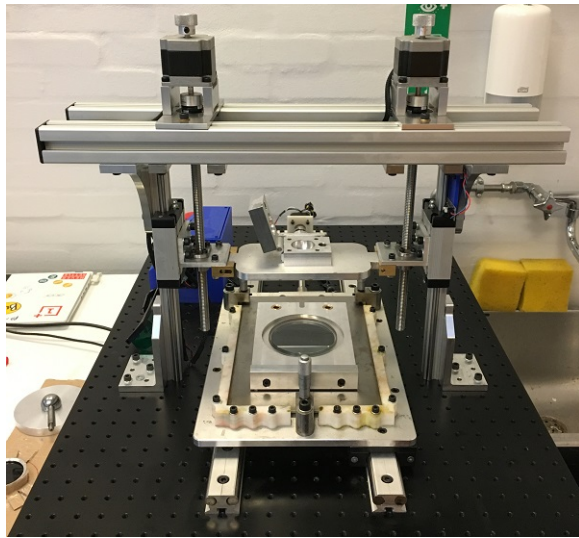


Figure 3: The UV light mask projection-based vat-photopolymerisation system at Department of Mechanical Engineering, Technical University of Denmark.

Parts manufacturing

The parts were manufactured in four different colours: red, black, white and natural. Two process parameters, i.e. layer thickness and UV light intensity, were differentiated while the exposure time was kept constant. The production included two stages; the first stage covered finding the process window for all of the resins. For this purpose, a simple die in the shape of the stage of the part was printed and the resulting appearance was evaluated qualitatively. It was possible to achieve satisfactory results using the same UV light intensity for all of the colours. Next, the target geometry was manufactured and it was immediately noticed that the features varied dramatically depending on the colour. It

was therefore decided to adjust the projector power according to different colours. The interval between the low and high level was kept the same. The parameters were chosen based on the qualitative observations, with the feasibility to print all of the features taken as a main criterion. Table 1 depicts the final UV light intensity used in the experiment.

Table 1: UV light intensities selected for DOE.

Colour	Radiant Intensity [mW]	
	Low level	High level
Natural	0.249	0.280
Black	0.280	0.304
Red	0.297	0.318
White	0.402	0.417

The course of the manufacturing process was based on a previous study and capabilities of the machine [1]. The second differentiated factor layer height, was varied at the levels of 10 μm and 12 μm . The remaining parameters were kept constant, according to Table 2.

Table 2: Fixed process parameters.

Parameter	Value
Exposure time [s]	1
Bottom layers exposure time [s]	12
Number of bottom layers	5

Geometrical measurements

The evaluation of the influence of process parameters was achieved by measuring the geometries with Alicona[®] Infinite Focus optical system; subsequently, a dimensional comparison with the original CAD design was carried out. The results were further analysed by means of design of experiment (DOE) based on which the characteristics such as shrinkage, accuracy, and the surface of the parts were associated with the pigmentation. Moreover, the influence of the colour on the post-curing of the samples was studied.

RESULTS AND DISCUSSION

Figure 4 shows the exemplary samples. The features were measured and compared to the nominal values of the CAD design separately, and the evaluation of the influencing factors was done by means of DOE. In this section, the performance of the process is represented by the Main Effects Plots for the deviations from nominal values of the

features. In order to unify the values of UV light intensity for the statistical analysis, the low and high level are represented by -1 and 1, respectively. The legends under the plots show the nominal values of the corresponding geometries.

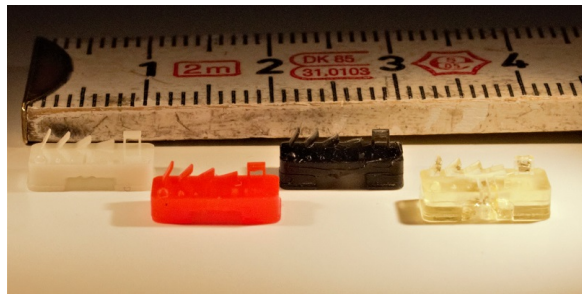


Figure 4: Exemplary samples.

Angles

For the analysis of the angles only the inclination of 30°, 45° and 60° was taken into account. The 15° angle was dismissed due to the excessive overcuring of the area between the angle and base of the samples (Figure 5). As it can be seen in Figure 6 the overall deviations have mostly positive values. The influence of the layer height and UV light intensity turned out to be insignificant.

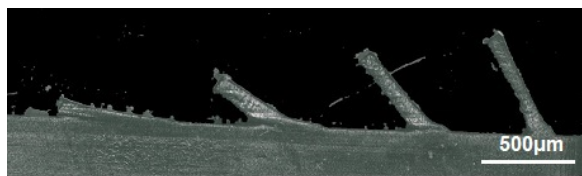


Figure 5: Overcuring of the area under the angle of 15°. Layer thickness: 12 µm; UV light intensity: 0.304 W; black resin.

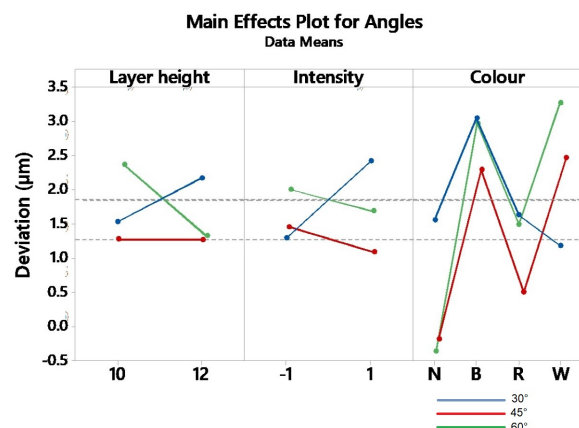


Figure 6: Main Effects Plot for deviations for the angles.

Grooves

For the evaluation of geometry of the grooves, the thickness of the gap in the middle of each groove was measured. When looking at the plot in Figure 7 it can be seen that in case of all of the thicknesses a similar trend occurs, i.e. the gaps of the grooves are wider at higher layer thickness and lower UV light intensities. For the grooves of 150 µm and 250 µm the discrepancies between the colours are small. In case of the groove of 50 µm the deviations are high for black and natural resin, which can be explained by higher UV light absorbency and resulting higher shrinkage [3]. Most of the smallest gaps were closed for the parts manufactured with white resin (Figure 8). This might be associated to the capillary forces, which prevent the resin flowing out during the cleaning process.

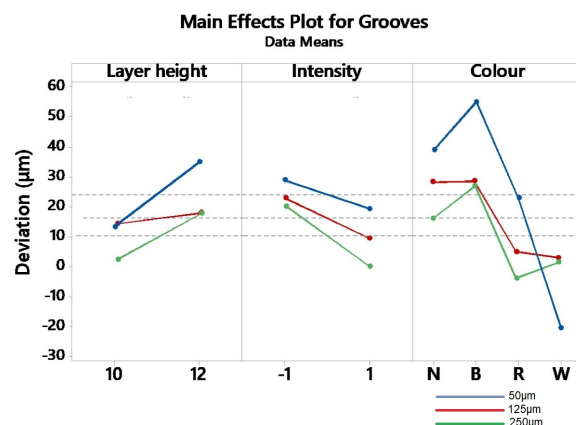


Figure 7: Main Effects Plot for deviations for the grooves.

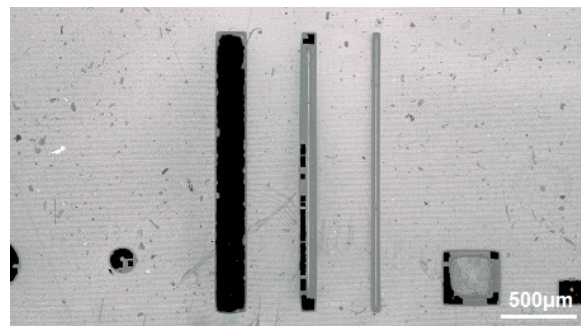


Figure 8: Overcured grooves. Layer thickness: 10 µm; UV light intensity: 0.402 mW; white resin.

Pillars

Two features were measured for evaluation of the geometry of the pillars: the width, seen from the top, and height seen from the side. The deviations are depicted in Figure 9 and 10. In almost all

of the cases the deviations had negative values, with the highest discrepancy or lack of the pillar of the highest aspect ratio. The UV light intensity had an insignificant impact on both height and width. The width of the highest aspect ratio feature turned out to be inversely proportional to the other two pillars when increasing the layer thickness. The geometries showed the smallest deviation in case of natural and red resins, whereas for black resin the pillars had smaller dimensions than the nominal values, due to the excessive shrinkage and cracking. In case of white resin the smallest pillars were missing in most of the samples.

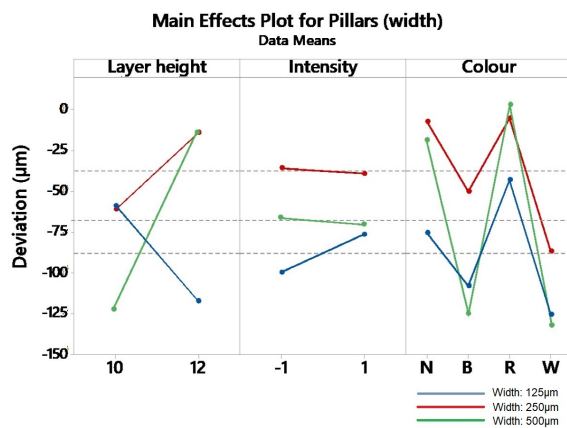


Figure 9: Main Effects Plot for deviations for the width of the pillars.

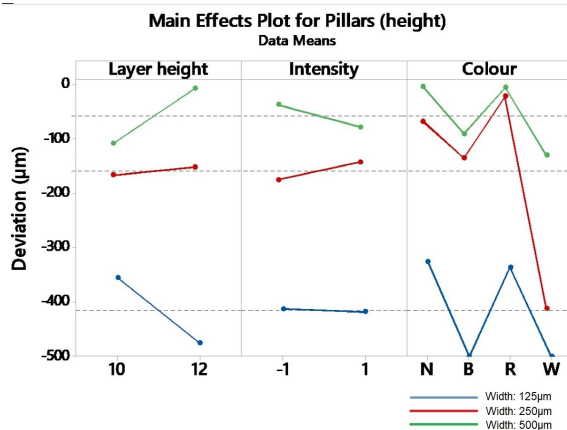


Figure 10: Main Effects Plot for deviations for the height of the pillars.

Spheres

No significant difference was found in case of manufacturing the spherical shapes. For all of the parameter combinations, all three spheres were produced in the shape and size very close

to the nominal geometries.

Overhang

The evaluation of the overhang was made by measuring the overhang height. The discrepancies for this geometry were the most prominent in case of the black resin, where the height of the overhang was significantly smaller than the nominal. This can be also associated with higher shrinkage, as in the case of grooves.

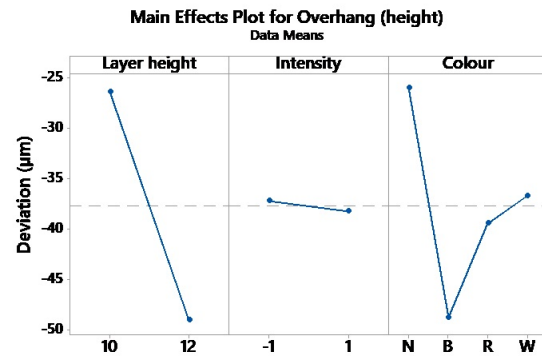


Figure 11: Main Effects Plot for deviations for the overhang.

Qualitative analysis

Aside from geometrical measurements of the features, an overall evaluation was made. It was observed that using different colours results in different quality of the surface of the samples. A fine and glossy surface was achieved in case of the red and white resin, where it was possible to observe the pixel texture, which can be seen in Figure 12 and 13. The surfaces in transparent and black samples were matt, as it can be seen in Figure 14.

In all of the samples produced with the black resin, there was a broad crack formation on the surface (see Figure 15). The cracks were formed almost immediately after the production.

Another observation was the difference of the stability of the resins towards the UV light. The highest discrepancies between the geometries were found in samples produced with white and transparent resins. The differences between the samples were particularly closed gaps for overhangs (see Figure 16), grooves and varying heights and widths of the pillars appearing randomly.

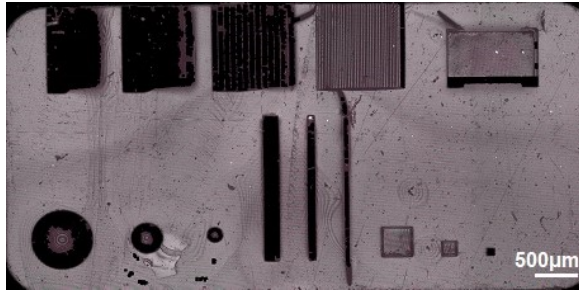


Figure 12: Top-view of the sample. Layer thickness: 10 μm ; UV light intensity: 0.297 mW; red resin.

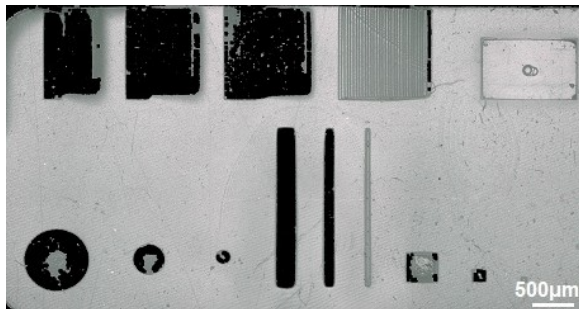


Figure 13: Top-view of the sample. Layer thickness: 10 μm ; UV light intensity: 0.402 mW; white resin.

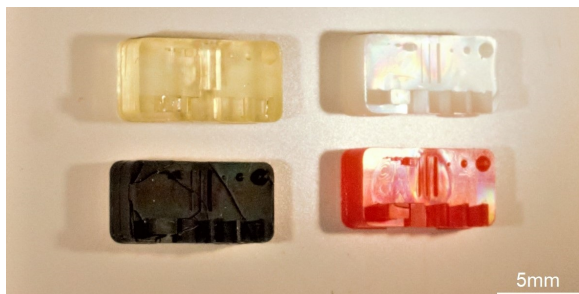


Figure 14: Top-view of the surfaces of the samples.

CONCLUSION

Based on the analysis it is evident that the colour of the resin has a significant influence on the resulting geometry of the parts produced in micro scale. This influence remains strong even with a well-established process window. Among all of resins, the red showed the best performance in terms of deviations, surface quality and stability towards the UV light. Black resin revealed the highest shrinkage. Parts produced with white and transparent resin revealed the highest discrepancies between the deviations of the features.

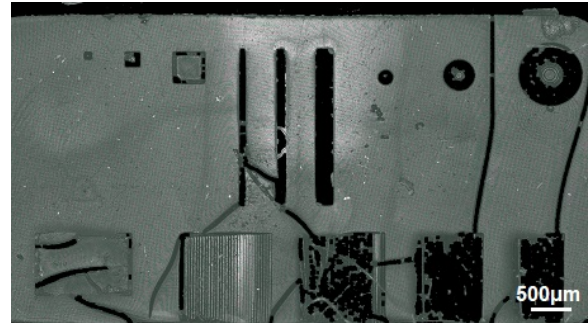


Figure 15: Top-view of the sample. Layer thickness: 12 μm ; UV light intensity: 0.280 mW; black resin.

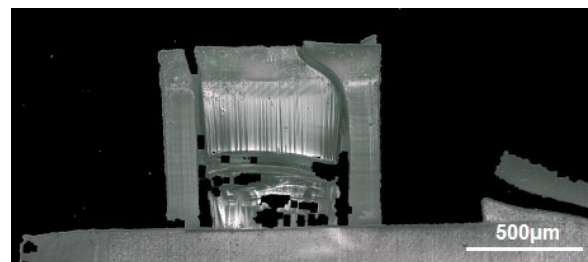


Figure 16: Overcured overhang. Layer thickness: 10 μm ; UV light intensity: 0.249 mW; natural resin.

By suitable pigmentation selection, it is possible to achieve fine geometry and lower the process time; therefore, it should be always taken into consideration when designing parts produced with additive manufacturing.

In light of this experiment, more work is recommended in order to further establish the influence of the colourant for photopolymerisation-based systems. The next step would be to differentiate the level of pigmentation in the resin blends to find the compromise between the accuracy of the parts and the colour intensity.

REFERENCES

- [1] Andersen F. W. Optimization of an Experimental DLP Platform by Construction and Process Studies. DTU Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark; 2018.
- [2] Bennet, J. Measuring UV curing parameters of commercial photopolymers used in additive manufacturing. Additive Manufacturing. 2017; 18: 203-212.
- [3] Chiu, S.-H., Wicaksono, S. T., Chen, K.-T., Chen, C.-Y., Pong, S.-H. Mechanical

and thermal properties of photopolymer/CB (carbon black) nanocomposite for rapid prototyping. *Rapid Prototyping Journal*. 2015; 21: 3: 262-269.

- [4] Davoudinejad, A., Ribo, M. M., Islam, A., Tosello, G. Direct fabrication of bio-inspired gecko-like geometries with vat polymerization additive manufacturing method. *Journal of Micromechanics and Microengineering*. 2018; 28: 1-10.
- [5] Macarie, L. and Ilia, G. Influence of Pigment Properties on UV-Curing Efficiency. *Journal of Applied Polymer Science*. 2007; 104: 247-252.
- [6] Moylan, S., Slotwinski, J., Cooke, A., Jurrens, K. Donmez, M.A. An Additive Manufacturing Test Artifact. *Journal of Research of the National Institute of Standards and Technology*. 2014; 119: 429-459.
- [7] Sepe, M. Understanding the Science of Color. *Plastics Technology*. 2016.

ISO 10360 pt 11: Progress towards an XCT verification standard

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Introduction

Since the 1970s' there has been growing use of X-ray CT in industry and academia in various roles.

The main role, until recently, has been in Non destructive testing with measurement only used as a simple check dimension.

Lately, there has been a growth of comparator type instruments where measurements of a workpiece can be traced via a reference object to a standard length. As the reference object has to be scanned at the same conditions as the sample this is a fairly slow method and is not ideally transferable between systems

Recently there has been a growth in the use of XCT for metrology and manufacturers have developed a number of Metrology grade instruments.

So far the only published document is the VDI 2630[1] (Figure 1) guidelines which give guidance on setting up an XCT metrology system but still leave areas which can be chosen independently. About 7 years ago this led to ISO TC 213 WG 10 accepting a new work package to develop a standard for verification of XCT metrology systems. This has been assigned to the ISO 10360 group of standards as part 11.

In the rest of this paper we will discuss the major areas of concern that have been discussed by the ISO committee and the latest status of the standard.

What is verification?

ISO 10360 pt 11 is a verification standard. This means that its aim is to allow users to verify the system manufacturers claims and compare between systems on a level playing field.

It is not a full calibration standard where every error source has been identified, modelled and handled.

The aim in the verification standard is to make sure that the test samples used will show an error if it is present in the system, so they should be

generally similar to typical work pieces. It is not necessary to be able to separate the errors.

i.e. If manufacturer A claims an MPE of $3+L/50$ and manufacturer B claims an MPE of $5+L/45$ then the standard will allow a user to test these claims under standard conditions with confidence that neither manufacturer is hiding an error source.

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	Computertomografie in der dimensionellen Messtechnik Leitfaden zur Anwendung von DIN EN ISO 10360 für Koordinatenmessgeräte mit CT-Sensoren	VDI/VDE 2630 Blatt 1.3 Entwurf
Accuracy of coordinate measuring machines – Characteristics and their testing – Guideline for the application of DIN EN ISO 10360 for coordinate measuring machines with CT-sensors		
Eingeführt im 2010-01-31 • vorzugsweise in Tabellenform als Datei per E-Mail an genau@vdi.de Die Vorlage dieser Tabellen kann abgerufen werden unter http://www.vdi-richtlinien.de/englische		
Computed tomography in dimensional measurement – Guideline for the application of DIN EN ISO 10360 for coordinate measuring machines with CT-sensors		
• in Papierform an VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik, Fachbereich Fertigungstechnik Postfach 10 11 38 40002 Düsseldorf		
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FIGURE 1. Cover page of VDI 2630 [1]

It is not necessary (or possible) to state that Manufacturer Bs' larger MPE is due to a specific source (spot size, beam hardening etc).

Comparability

One of the main issues that had to be resolved was comparability. Most of the early 10360 parts were related to tactile co-ordinate measuring systems such as CMMs. These worked with a finite set of points to create the surfaces. XCT and some later optical techniques can generate many thousands of points per surface.

This led to the question of how to make the standards comparable so that measurements on a CMM were (in principle) compatible with those taken with XCT or optical probes.

While this has not been fully resolved two steps have been taken;

- 1) The large number of points can be reduced using patches (areas of the surface) which can be reduced to a single point. By choosing 25 such patches carefully the results can be compatible with the 25 point surfaces derived from a tactile measurement.
- 2) New parameters, for certain measurands (e.g. Probing error of form) are introduced. These use 95% of all available points to derive a surface for measurement and will give different results to the patch method.

There are ongoing discussions about which is better and whether a hybrid approach should be used, where the 95% of points are used to find e.g. the centre of the sphere to which the 25 patches are then referred.

One of the problems with the patch method is defining the size of the patch, it needs to contain enough data to define a single point well, but if the surface is a sphere can you use that knowledge to fit a spherical cap or should you use no a-priori knowledge and fit a best surface of whatever type.

In order to produce a draft standard for CD ballot a certain set of assumptions have been taken which are self consistent but may need adjustment.

Penetration & Beam hardening

One of the key parameters of an CT system is its penetration, this is set by the maximum kV primarily. This means that for any system there will be a maximum length that can be penetrated (of a given material) and this is a parameter that should be quoted by the manufacturer.

Related to this is the beam hardening issue, this arises when an X-ray source is polychromatic (which most microfocus and minifocus sources used in industry are), the penetration length

varies with the kV and so the simple relationship between path length and resulting intensity

$$I = I_0 e^{-\mu t} \quad (1)$$

Is incorrect. The attenuation μ depends on kV and so this equation has to be considered a sum over the spectrum.

$$I = \sum_E I_{0,E} e^{-\mu_E t} \quad (2)$$

Most reconstruction algorithms assume equation (1) is true but include a beam hardening correction, usually a measured fit of actual grey value to corrected grey value or similar

In order to deal with this the new standard must include sufficient differences in path length to require the manufacturers beam hardening correction to be needed in order to get the correct results.

For this reason the simple pair of spheres sample with a calibrated centre-centre distance is not, on its own, a suitable sample as the path length is effectively fixed for any distance measurement.

The VDI 2630 suggests using a combination of spheres combined with a step cylinder or similar sample. However, this requires multiple scans of the different samples.

The latest standard is suggesting a hole plate which includes many different path lengths as well as many different directions for measurement.

This has some practical drawbacks, firstly that the accuracy to which the cylinders must be measured is very high and the size of the cylinders for systems at lower kVs is small and secondly, the size of the hole plate can be very small itself for low kV in some materials.

A refinement of this under discussion (suggested by NIST) (Figure 1) is to place a sphere into each hole so that the measurements are easier to make but the path lengths are still present, this reduces the need for high accuracy cylindrical holes in the hole plate as the spheres can be measured more accurately with the hole plate removed. However, it doesn't address the limitation that the size of the hole plate must be chosen so that it can be fully penetrated at

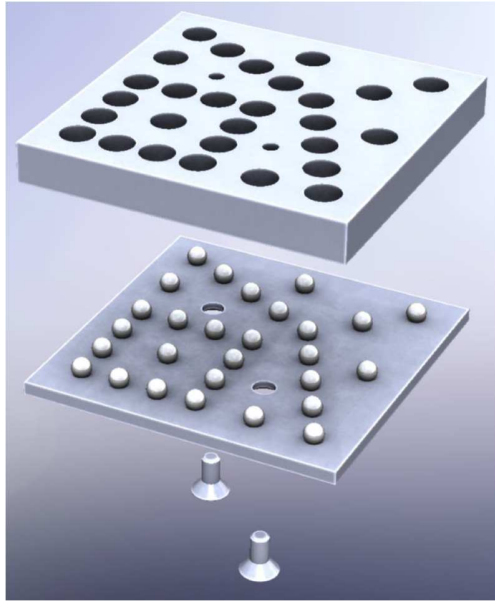


FIGURE 2. Illustration of ASME suggested combined Hole and sphere sample[2]

Structural resolution

Another key area of concern is the structural resolution. This is generally taken to mean the smallest measurable structure in a scan.

In general this is not the same as the spatial resolution due to the Voxel size or the spot size of the size, it is influenced by these quantities but also includes aspects of the surface determination and object structure.

However, it is an important characteristic as the use of filtering on the CT data will directly affect the structural resolution and so it can be used to check for excessive filtration to 'improve' data quality.

Unfortunately this is not easy to define and measure in CT, the original VDI guide includes a method first used by University of Padua which utilises two touching spheres [3,4].

In this method (see Fig 3) Two touching spheres are scanned. The bulk of the spheres well away from the contact point can be used to fit the spheres and so find the plane of contact. On this plane there should be a single point for the contact but system resolution will degrade this and there will be a circle of confusion, defined as the smallest circle that includes all points. At the diameter of this circle the distance between the spheres is measured, this is the structural resolution as it is the smallest distance that can be measured.

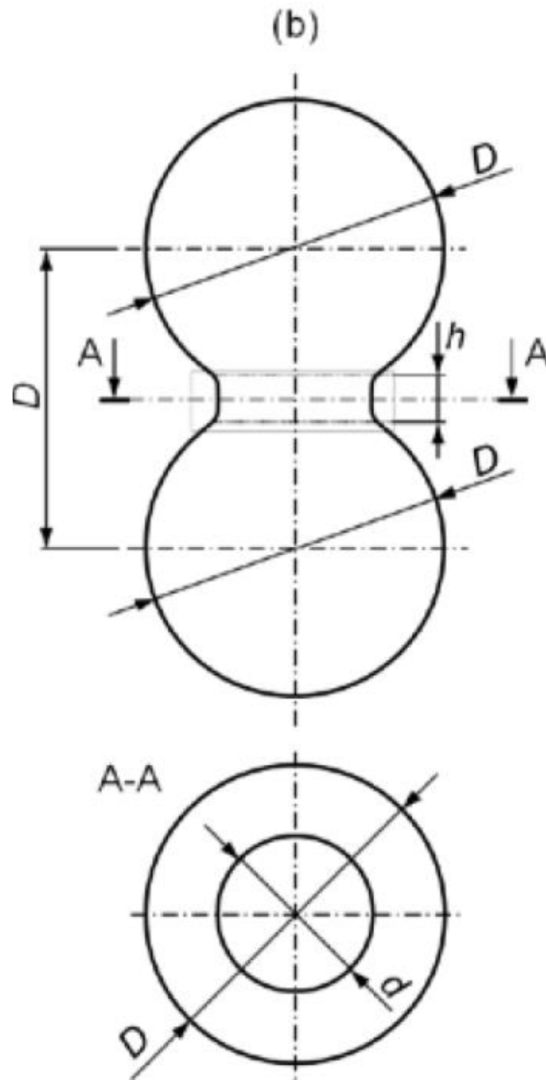


FIGURE 3. Outline of touching spheres method for structural resolution measurement. The structural resolution h of the system is the separation of the spheres at the radius of the region of confusion between two touching spheres.

This method gives an indication of the structural resolution but is dependent on the object shape being spherical, which is not typical of real measurement pieces.

A range of alternatives were reviewed by PTB and FMT [6] in particular FMT proposed an Aperiodic Spatial Frequency Standard (ASFS) [7,8] The concept of which is

- 1) Measure a standard with an aperiodic profile
- 2) calculate amplitude transfer function in Fourier space
- 3) Defined structural resolution as reciprocal of spatial limit frequency for 50% amplitude transfer (cf the filter λ_s , λ_c and λ_f definition of ISO 4287)

It was shown that this concept worked.
An alternative approach suggested by PTB [6] is the differential geometry approach

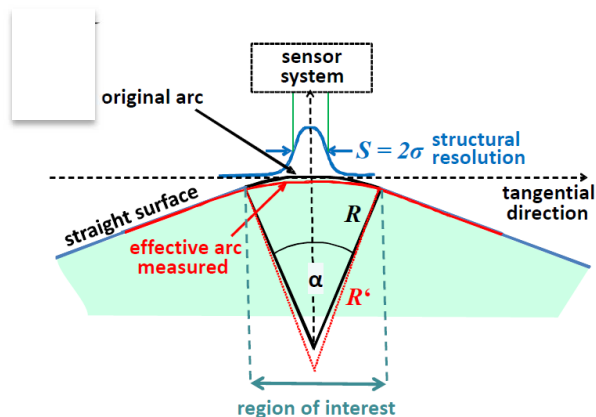


FIGURE 4. Outline differential geometry method for structural resolution (S) measurement.

This approach measures the radius of a known curve using a series of gaussian filters and extracts the best measurement as being the Gaussian filter with a FWHM of $2S$.

The method is sensitive to variations in the choice of the centre of curvature and radius and these lead to limits on applicability.

PTB have designed a test object and tested it on their Nikon Metrology XT H 225 ST getting a values of the order of 4-5 microns for the structural resolution with voxel sizes of approximately 2 microns.

Latest status

While there are a number of issues still to be resolved, and these will be discussed in more detail at the conference, the standard has reached provisional committee draft stage (CD) and is being circulated for national comments to be added over the summer.

These comments will be considered and the standard updated at the next TC213/WG10 meeting scheduled for September.

REFERENCES

- [1] VDI/VDE, VDI/VDE 2630 'Computed tomography in dimensional measurement'
- [2] Schlecht J, communication to ISO TC213/WG10 meeting 2016
- [3] Carmignato et al.: CT for Industrial Metrology – Accuracy and Structural Resolution of CT Dimensional Measurements. iCT 2012
- [4] F Zanini and S Carmignato 2017 Meas. Sci. Technol. 28 114002
- [5] Structural Resolution in Dimensional Metrology
- [6] Fleßner et al Report about work of FMT and PTB in the Field Coordinate Metrology (here in particular CT) ISO TC213 WG10 London 2018
- [7] M. Fleßner et al.: CT measurements of microparts: Numerical uncertainty determination and structural resolution. In: AMA Conferences 2015 - SENSOR 2015 and IRS² 2015. doi: 10.5162/sensor2015/C8.2
- [8] M. Fleßner et al.: Determination of metrological structural resolution of a CT system using the frequency response on surface structures. In: MacroScale, 2014. doi: 10.7795/810.20150223B

MACHINE METROLOGY FOR A METAL LASER POWDER BED FUSION MACHINE

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INTRODUCTION

Additive manufacturing (AM) is considered a disruptive technology with the potential to radically alter product design and to introduce paradigm changes across a broad range of industries and applications. The precision engineering and metrology communities are not immune to AM's impact as new techniques and systems are needed to characterize the equipment, processes, materials and parts involved in or produced by AM. Final part form and finish are generally considered to be deterministic in traditional subtractive machining using a range of metrology techniques developed and refined within the precision engineering community over the previous decades. Material properties are also typically assumed directly from the original raw feedstock. Additive manufacturing, however, introduces a paradigm shift wherein the manufacturing system deposits material at a desired location, building onto existing materials and structures. Final part geometry, therefore, becomes an outcome of the positioning accuracy of material placement, the physics of

the deposition and fusing processes at each material location, the deformation from residual material stresses, and the cumulative errors of the build process.

Researchers over the past couple of decades have developed metrology artifacts typically suited to their process, material and/or performance metric of interest [1]. Our own prior work [2] paralleled many of these efforts as we developed artifacts for characterizing process accuracy, form, overhangs, surface texture and minimum feature size. A proper understanding and characterization of machine performance, however, remains necessary to optimize process inputs, to maintain process control and to decouple process influences for greater process understanding. Various aspects of a metal laser powder bed fusion (L-PBF) machine have been characterized, both to quantify and improve equipment and process performance.

Metal L-PBF operates by spreading a layer of metal powder across a flat build plate, Figure 1. A laser, typically a continuous wave fiber laser operating with a $1\mu\text{m}$ wavelength, scans across

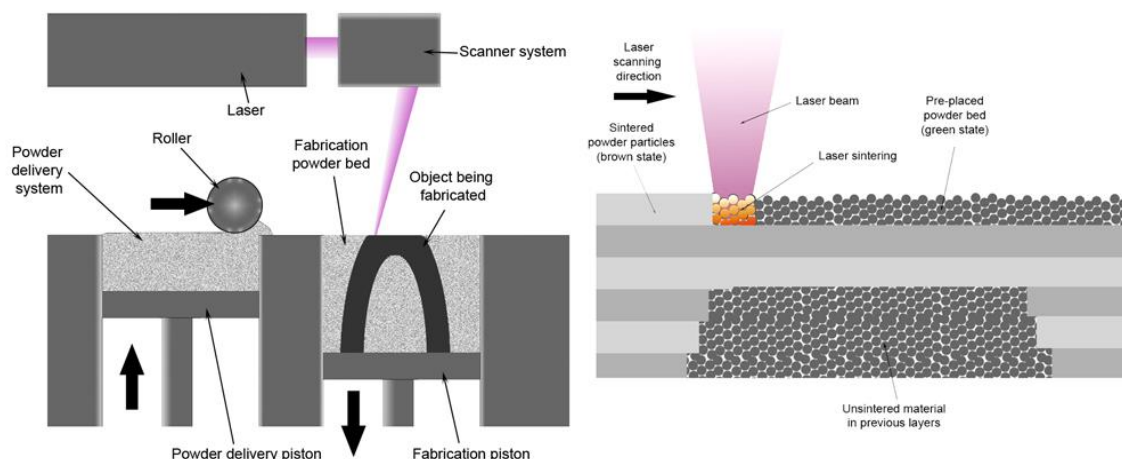


FIGURE 1. Schematic of metal laser-powder bed fusion [3].

the powder surface melting and consolidating powder into the desired part geometry. The behavior of the laser-material interaction zone, i.e. the melt pool, is critical in establishing part quality and integrity. While the laser-material interaction zone is highly dynamic [4], establishing a relatively constant melt pool is generally desired through a part build. Multiple factors influence the melt pool, ex. powder feedstock or part geometry, but the explored work is focused solely on factors associated with the machine itself.

A plethora of process inputs are associated with and can be varied in a L-PBF system. Work, however, has focused on the motion of the build plate piston and on the performance of the fiber laser since these elements control the applied powder layer thickness and the laser energy deposited into the melt pool, respectively. Experience with the process has also shown that changes to the powder layer thickness and the incident laser power have a significant impact on process and material quality.

MOTION AXES

While metrology of conventional machine tools is commonly focused on motion errors associated with multiple linear and rotary axes, the L-PBF machine under investigation relies on relatively simple motion axes for powder spreading and laser positioning. Powder spreading is performed using a rotating roller which moves in a horizontal axis parallel to the machine's build plate. The vertical position of the roller is fixed in the machine, and so it serves as a reference for zeroing the build plate location with each build. Powder is stored in a hopper below the roller, Figure 1, and is fed into the roller's path for spreading through upward vertical motion of the supply piston. While motion of the supply piston controls the metering of powder for spreading, its accuracy is not particularly impactful to part quality if enough powder is available to fully cover the build plate surface. Thus, powder layer thickness is driven predominantly by the motion of the build plate piston, a ball-screw driven stage with 100mm of travel. Short and long-range build plate motion was measured by mounting Keyence LJ-V7020 and LJ-V7200 laser profilers respectively inside the build chamber and focused onto a build plate surface. Short range motion was obtained moving the build plate up and down 100 μ m in 10 μ m steps while long range motion was

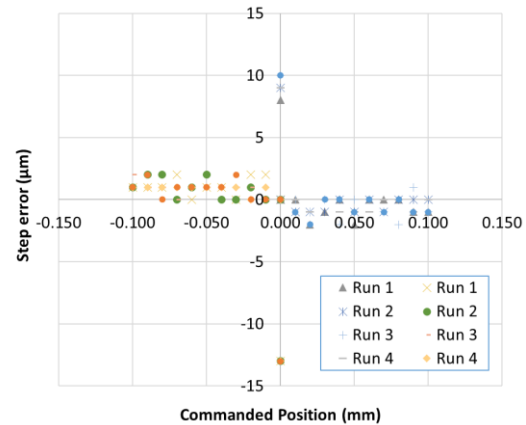


FIGURE 2. Short-range build piston position errors.

collected in 1mm steps over 74mm of travel. Figure 2 plots the error in each step of the short-range measurement. During single direction motion, step errors are below 2 μ m, less than 10% of the 30 μ m nominal powder layer thickness utilized in printing. 10 μ m of error is observed when the stage changes directions. Such errors are believed to be acceptable for process performance since powder particle sizes vary by more than 2 μ m, with tails beyond 10 μ m of the mean diameter.

FIBER LASER

While powder layer is clearly an important process parameter, laser performance has been observed to represent one of the most crucial factors for optimizing and insuring a robust process. Work to characterize the L-PBF laser source was begun by using an Ophir L50(300)A-LP1 power meter to measure laser power as a function of the commanded machine input. Figure 3 shows the resulting power curve which

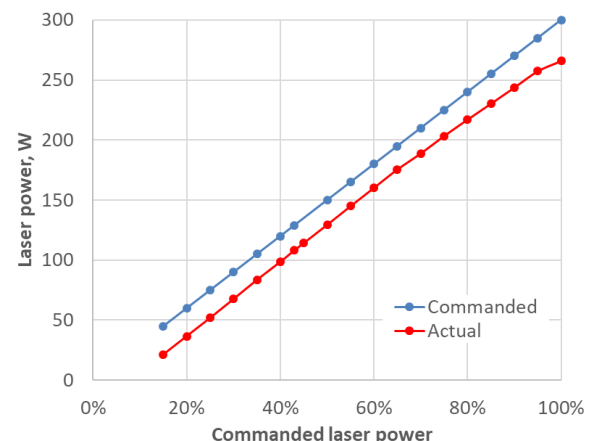


FIGURE 3. Fiber laser power curve.

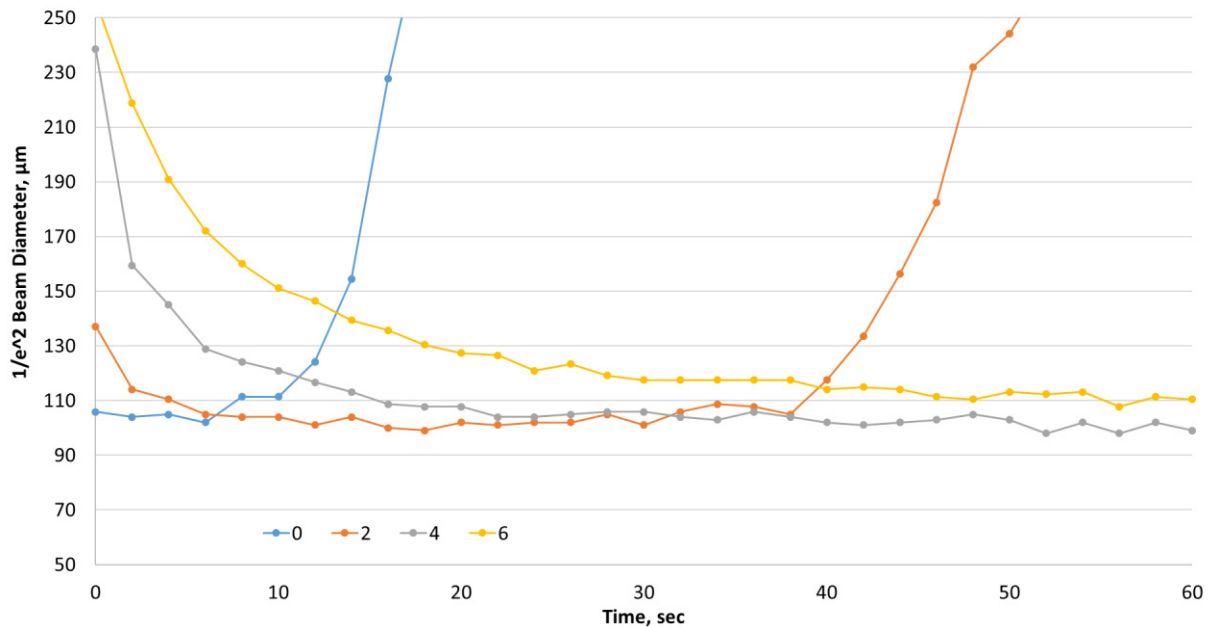


FIGURE 4. Fiber laser 1/e² diameter variation with time and focus offset.



FIGURE 5. Test part printed using nominal focus position (left) and modified focus position after beam characterization (right).

is essentially linear and shows a roughly 25W difference between the commanded power and the laser output. It is commonly observed in the literature that researchers only publish commanded laser settings. Infrequently are actual energy levels reported, a problem for the research community. While insertion of a power meter into a commercial L-PBF systems can require some engineering for initial access; once established, a laser power curve can be measured in a matter of minutes and should be routinely checked to monitor system state of health.

A more involved, and informative, laser characterization step is to measure the beam energy profile. This was performed using an Ophir Spiricon SP928 beam profiler to quantify

beam shape and temporal variations during operation. Figure 4 shows the laser's 1/e² beam diameter for nominal operation at 103W as a function of time and focus offset, i.e. location of the build plate relative to beam focus. Significant variation in laser focus is observed due to lens distortion from heating of the f-theta optic in operation. Operation at nominal focus, i.e. a 0mm focus offset, represents an unstable process wherein deviation from optimal occurs in a matter of only a few seconds. Attempts to perform a complex verification build, Figure 5, was initially unsuccessful due to this process instability. Adjusting the focus offset just 4mm, however, dramatically improved process performance and enabled the successful printing of the verification build, Figure 5. While process adjustments proved useful in the interim, an

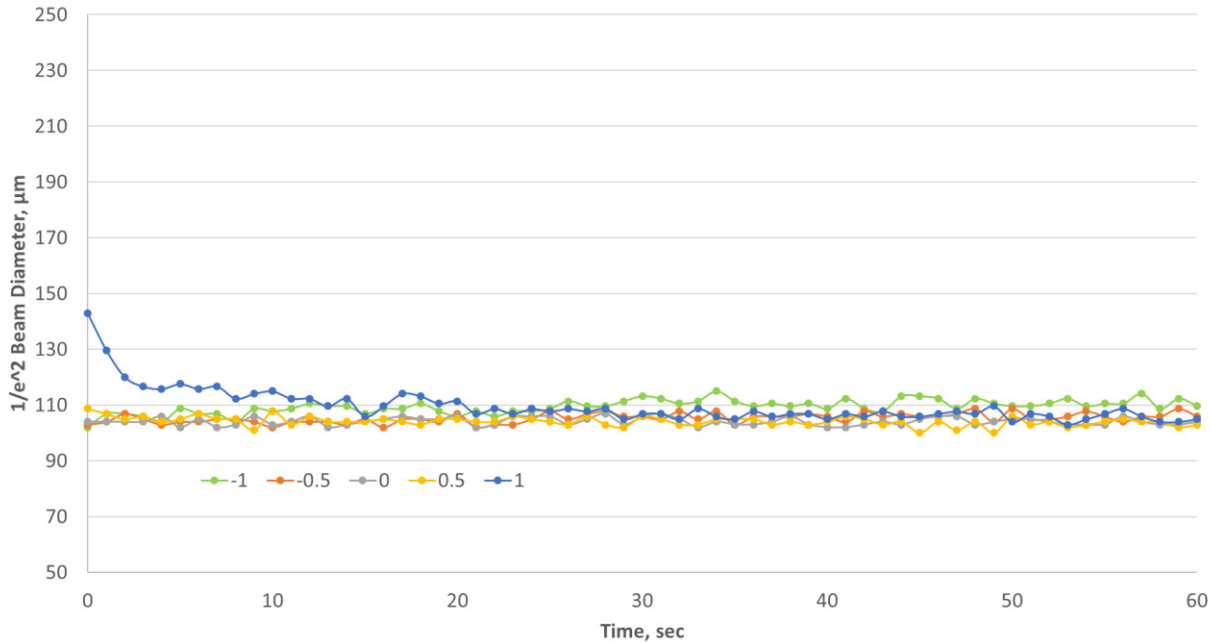


FIGURE 6. Fiber laser 1/e² diameter variation with time and focus offset after f-theta lens upgrade.

upgrade of the system's f-theta lens by the OEM has significantly reduced thermal distortions, Figure 6, and improved laser stability and reliability.

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This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

REFERENCES

- [1] Moylan, S., Slotwinski, J., Cooke, A. Jurrens, K., and Donmez, M., "Proposal for a standardized test artifact for additive manufacturing machines and processes," Proc. of the 23rd Int. Solid Free Form Symposium, Austin, TX, August 2012, pp. 902-920.
- [2] Jared, B., Tran, H., Saiz, D., Boucher, C., and Dinardo, J., "Metrology for Additive Manufacturing Parts and Processes", Proc. of the ASPE Topical Meeting on Dimensional Accuracy and Surface Finish in Additive Manufacturing, Berkeley, CA, April 2014.
- [3] <https://commons.wikimedia.org/w/index.php?curid=4032088>, by Materialgeenza - own work, CC BY-SA 3.0.
- [4] Khairallah S, Anderson A, Rubenchik A, King W., "Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones," Acta Materialia, 2016, vol. 108, pp. 36-45.

MEASUREMENTS AND SIMULATIONS OF THE CROSS-SECTION OF THE PRINTED STRANDS IN FUSED FILAMENT FABRICATION

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ABSTRACT

We measure and simulate the shape of an extruded strand in Fused Filament Fabrication; an additive manufacturing method where a solid thermoplastic material is melted and extruded through a nozzle in order to create a layered three-dimensional object. The prediction of the strand shape is essential in order to estimate the porosity, the surface roughness, and the dimensional accuracy of the fabricated parts. Using optical microscopy, we quantify the dimensions of the strand cross-sections, for different printing conditions. For the first time, we compare experimental measurements of the strand cross-section with numerical results of three-dimensional computational fluid dynamics simulations. The numerical model predicts the effect of change of the layer height on the strand morphology and shows good agreements with the measurements.

INTRODUCTION

Fused Filament Fabrication (FFF) is an extrusion-based additive manufacturing (AM) technique, in which the raw material is fed into the liquefier that melts it and extrudes it in the form of a strand [1]. The subsequent strands and layers bond together by means of a temperature-driven diffusion process [2] to form a three-dimensional object. FFF parts have traditionally been used for prototyping and rapid tooling, but recent developments have enabled the process to produce end-use products.

Extrusion-based AM is easy to operate when compared with other AM methods. The machine cost can be very low what has been proven by the success of the open-source 3D printers. However, the fabricated parts generally suffer from a large surface roughness [3], low dimensional accuracy [4], and relatively low tensile strength due to weak inter-layer bonding [5]. In order to mitigate these problems, a large number of studies have focused on optimizing the printing conditions and finding empirical relations

with the properties of the part. A review of those studies can be found in [6].

The part properties depend on its microstructure and, in particular, the strand shape. The importance of the strand shape is seen in the studies that investigated the porosity [7], the surface finish [8], the inter-strand bonding [9], and the cooling rate of the part [10]. The development of the strand shape is related to the deposition flow of the extruded material, which has recently gained attention in numerical studies of the FFF process, using the Computational Fluid Dynamics (CFD) approach [11, 12, 13, 14, 15, 16]. However, many of these studies lack experimental data in order to validate their results.

In this work, we measure the strand cross-sections for different printing conditions and we compare the results with three-dimensional CFD simulations. We quantify the changes in the strand shape as a function of the gap height between the substrate and the nozzle orifice.

METHODOLOGY

Experimental measurements

Figure 1 shows the assembly model of the open-source 3D printer used in the study (BQ Hephestos 2). The nozzle diameter D was 0.4 mm, and the input material was polylactic acid (PLA) extruded at the temperature of 200 °C. We investigated the influence of four gap heights (distance between the nozzle and the substrate); see Table 1. The printing velocity was $V = 20$ mm/s. The toolpath was controlled by specifically prescribed G-code. The measurement procedure of the strand cross-section included: (1) printing a single strand at the desired gap height, (2) cutting the strand, (3) grinding the cross-section on a rotating machine using a sandpaper with the granulation 4000, (4) taking optical micrograph of the cross-section, (5) analyzing the micrograph in MATLAB. The procedure was repeated three times for each gap height. The uncertainty of the measurement method was around 5 μm .

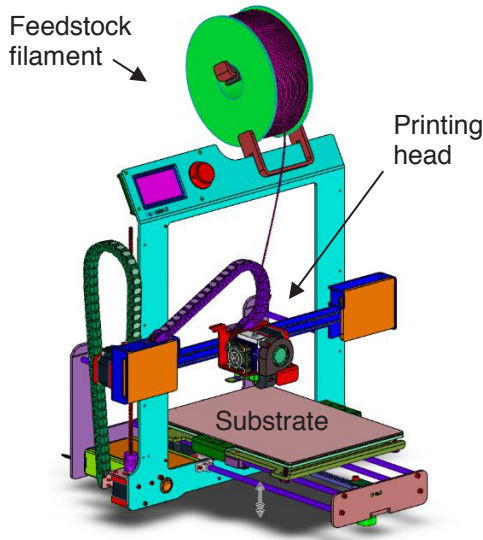


FIGURE 1. Assembly model of the 3D printer. Open-source CAD model available at [17].

The printing resolution of the BQ Hephestos 2 machine is 50 μm , according to the data sheet, which was an order of magnitude less than the expected height and width of the strand. Nevertheless, the mechanical systems of most of the low-cost desktop 3D printers operate in an open control loop, which means that the actual values of the printing conditions are neither monitored, nor corrected. To mitigate these problems, we conducted a calibration procedure before running the experiments. The calibration aimed on eliminating a systematic error in the filament feeding rate and in the positioning of the printing head above the substrate (which were crucial for the accuracy of the measurements).

We started by calibrating the filament feeding rate V_f , which is related to the cross-sectional area A of the strand by the virtue of volume conservation as

$$C_f \cdot V_f \frac{\pi D_f^2}{4} = VA \quad (1)$$

where D_f is the filament diameter and C_f is the calibration factor that we wanted to find. In order to compare the measurements with the simulation, it was convenient to relate the strand cross-sectional area to the volumetric flux inside the nozzle U (i.e. average velocity inside the nozzle)

$$VA = U \frac{\pi D^2}{4} \quad (2)$$

where U was set to 20 mm/s. By comparing the measured cross-sectional areas of the printed strands with the expected nominal values (Equation 2), we found an average calibration factor of 1.18.

Next, we calibrated the printing head position above the substrate. We started by printing a single strand with a variable gap height above the substrate (see Figure 2). The material was extruded along a distance of 190 mm, starting at the gap height set to $2.5D$, and finishing at $0.6D$. We measured the strand height at different cross-sections, every 10 mm, and plotted the values as shown in Figure 3. The corresponding G-code settings are also presented in the graph. It was found that the strand height decreases linearly along the printed strand, as expected; however with a different slope than the G-code setting and with a large offset. These observations indicate two faults in the printing head positioning: (1) the printing head axis was not parallel to the substrate; (2) the vertical position of the printing head had a systematic offset. By performing all the following measurements at only one location on the substrate, we did not need to correct for the parallelism error. The reference location was chosen to be at the distance along the printed strand where the measured strand height equaled $0.8D$ which was somewhat in the middle of the inspected range. The systematic offset was corrected by adding a constant to the G-code setting. The constant was equal to the difference between the measured strand height and the G-code setting at the reference location (see Figure 3).

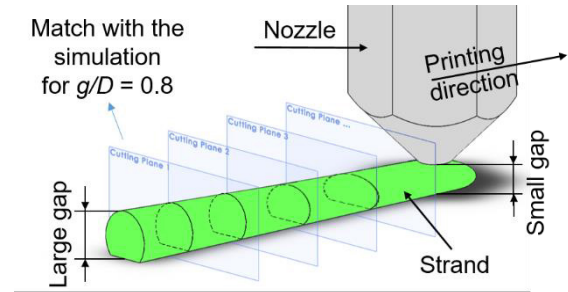


FIGURE 2. Calibration procedure of the vertical distance of the printing head above the substrate. Printing of a single strand with a variable gap height.

TABLE 1. Printing conditions in the experiments.

Variable	Symbol	Unit	Value
Gap height (nozzle position above the substrate)*	g	mm	0.40, 0.32, 0.24, 0.16
Nozzle diameter	D	mm	0.4
Normalized gap height	g/D	-	1.0, 0.8, 0.6, 0.4
Extrusion volumetric flux (average velocity inside the nozzle)*	U	mm/s	20
Printing head velocity	V	mm/s	20
Normalized printing head velocity	V/U	-	1.0
Filament diameter	D_f	mm	1.75 ± 0.05
Extrusion temperature	T	°C	200

*Values after the calibration procedure

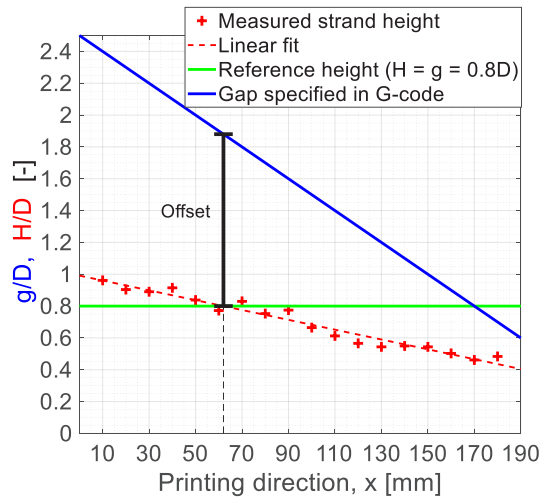


FIGURE 3. Measured height of the strand and the gap setting during the calibration procedure.

Numerical model

The flows of the strand deposition were simulated using a CFD model implemented in ANSYS Fluent R18.2 [18] that had been previously presented in [15]. The geometry of the model consisted of a stationary cylindrical nozzle with a diameter D that extrudes a material onto a moving substrate with velocity V (see Figure 4). The gap height is denoted g . As the deposition process was in a steady state, the opposite configuration, when the nozzle moves and the substrate is stationary, is equivalent to the implemented case. The flow was modeled as isothermal, incompressible and Newtonian. Although included in the simulation, the inertial and gravitational forces are negligible, due to creeping nature of the flow. Thus, the process conditions are fully described by the ratios g/D and V/U , where U is the average velocity at the nozzle inlet (i.e. the extrusion volumetric flux).

The walls of the nozzle and the substrate were specified a no-slip boundary condition while the remaining boundaries of the simulation domain were outlets.

The governing equations of the flow (i.e. the momentum and the mass conservation) were solved using the transient coupled pressure-velocity solver with an implicit in time scheme. The free surface of the material was tracked using a coupled level-set/volume-of-fluid method. The detailed description of the numerical model is available in [15].

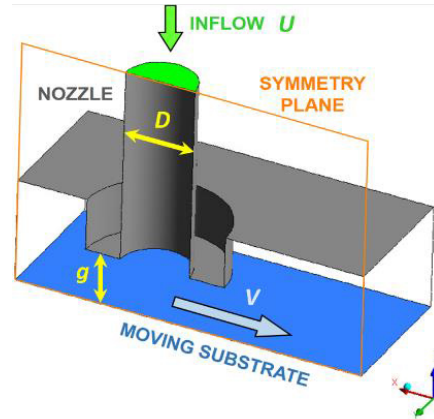


FIGURE 4. Extrusion nozzle implemented in the numerical model [15].

RESULTS AND DISCUSSIONS

The measured cross-sections of the strands are compared with the results of numerical simulations. The first column in Figure 5 represents the predicted strand shape at the outlet boundary of the numerical model. The next columns show micrographs of three strands independently printed, under the same process conditions.

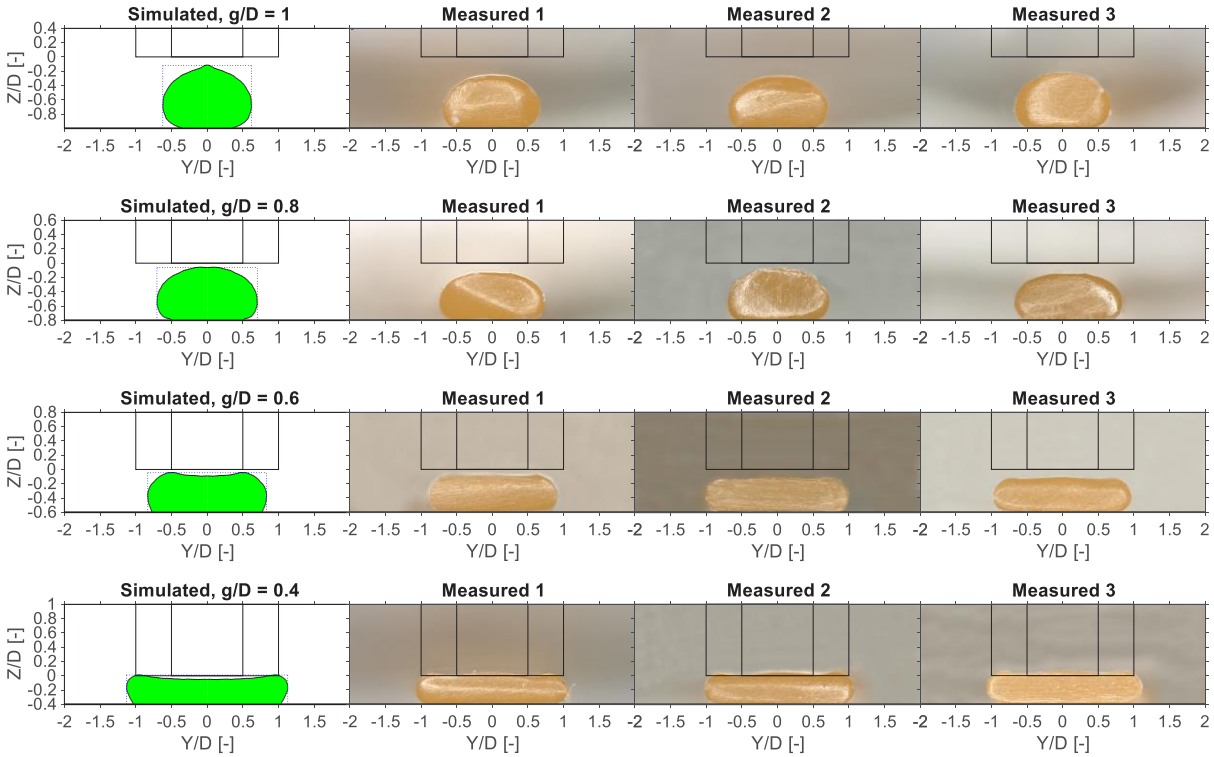


FIGURE 5. Simulated and measured strand cross-sections deposited at different gap heights.

We observed that decreasing the normalized gap height g/D leads to flattening the oval shape of the strand into a rectangular shape with rounded corners. The numerical results are in very good agreement with the measured strand shapes. The model captures the first order effect of flattening the strand when the gap height is decreased. In Figures 6 and 7, the strand height and the strand width are plotted as a function of the normalized gap height. In addition, we plotted an idealized solution of the strand shape based on the volume conservation and assuming an elliptical strand profile [15]. In overall, the proposed model gives better predictions of the height and width of the strand than the idealized solution.

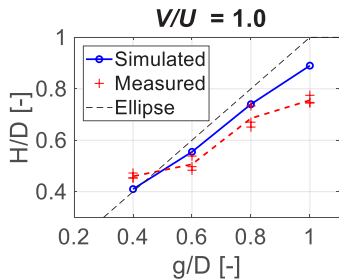


FIGURE 6. Measured and simulated strand height.

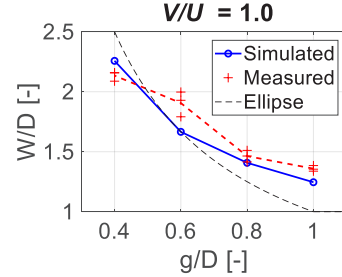


FIGURE 7. Measured and simulated strand width.

CONCLUSIONS

We have measured and simulated the cross-sections of strands printed by Fused Filament Fabrication, for different gap heights. The numerical results show very good agreement with the experimental data. The model predicts well the trend of the strand flattening when the gap height is decreased. Our results suggest that the strand shape can vary significantly depending on the processing conditions. Accurate predictions of the strand morphology can be used to enhance control over the surface roughness, the porosity, and the dimensional accuracy of the FFF manufactured parts.

ACKNOWLEDGMENTS

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REFERENCES

- [1] Wohlers T, Campbell I, Diegel O, Kowen J, Caffrey T. Wohlers Report 2017: 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report. Wohlers Associates. 2017.
- [2] Li L, Sun Q, Bellehumeur C, Gu P. Investigation of bond formation in FDM process. Solid Freeform Fabrication Symp. Austin, TX: 2002.
- [3] Ahn D, Kweon JH, Kwon S, Song J, Lee S. Representation of surface roughness in fused deposition modeling. Journal of Materials Processing Technology. 2009; 209: 5593-5600.
- [4] Boschetto A, Bottini L. Accuracy prediction in fused deposition modeling. International Journal of Manufacturing Technologies. 2014; 73: 913-928.
- [5] Ziemian C, Sharma M, Ziemian S. Anisotropic Mechanical Properties of ABS Parts Fabricated by Fused Deposition Modeling. Mechanical Engineering. InTech. 2012.
- [6] Mohamed OA, Masood SH, Bhowmik JL. Optimization of fused deposition modeling process parameters: a review of current research and future prospects. Advance Manufacturing. 2015; 3: 42-53.
- [7] Li L, Sun Q, Bellehumeur C, Gu P. Composite Modeling and Analysis for Fabrication of FDM Prototypes with Locally Controlled Properties. Journal of Manufacturing Processes. 2002; 4: 129-141.
- [8] Boschetto A, Giordano V, Veniali F. Modelling micro geometrical profiles in fused deposition process. The International Journal of Advanced Manufacturing Technology. 2012; 61: 945-956.
- [9] Sun Q, Rizvi G, Bellehumeur C, Gu P. Effect of processing conditions on the bonding quality of FDM polymer filaments. Rapid Prototyping Journal. 2008; 14: 72-80.
- [10] Costa S, Duarte F, Covas J. Estimation of filament temperature and adhesion development infused deposition techniques. Journal of Materials Processing Technology. 2017; 245: 167-179.
- [11] Du J, Wei Z, Wang X, Wang J, Chen Z. An improved fused deposition modeling process for forming large-size thin-walled parts. Journal of Materials Processing Technology. 2016; 234: 332-341.
- [12] Xia H, Lu J, Dabiri S, Tryggvason G. Fully Resolved Numerical Simulation of Fused Deposition Modeling. Part I - Fluid Flow. Rapid Prototyping Journal. 2018; 24: 463-476.
- [13] Xia H, Lu J, Tryggvason G. Fully Resolved Numerical Simulations of Fused Deposition Modeling. Part II. Solidification, Residual Stress, and Modeling of the Nozzle. Rapid Prototyping Journal. In peer-review, 2017.
- [14] Liu J, Anderson KL, Sridhar N. Direct Simulation of Polymer Fused Deposition Modeling (FDM) - An implementation of the Multi-Phase Viscoelastic Solver in OpenFOAM. International Journal of Computational Methods. 2018; 15: 1844002.
- [15] Comminal R, Serdeczny MP, Pedersen DB, Spangenberg J. Numerical modeling of the strand deposition flow in extrusion-based additive manufacturing. Additive Manufacturing. 2018; 20: 68-76.
- [16] Serdeczny MP, Comminal R, Pedersen DB, Spangenberg J. Numerical Study of the Impact of Shear Thinning Behaviour on the Strand Deposition Flow in the Extrusion-based Additive Manufacturing. Proceedings of Euspen's 18th International Conference and Exhibition. Venice: 2018.
- [17] BQ, "GitHub - BQ/Hephestos 2 Repository," [Online]. Available: <https://github.com/bq/hephestos-2>.
- [18] ANSYS® FLUENT R18.2, ANSYS FLUENT Theory Guide. © ANSYS, Inc. 2017.

EFFECT OF PROCESS PARAMETERS ON DIMENSIONAL ACCURACY OF DOWN-FACING SURFACES IN SELECTIVE LASER MELTING OF Ti6Al4V

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INTRODUCTION

Additive Manufacturing (AM) technologies have rapidly spread to cover a wide range of industrial applications, such as aerospace, automotive and biomedical [1]. This is due to their inherent capability to produce parts with complex geometries in short lead times, which shows great potential to strengthen the profitability of supply chains [2]. However, one constraint on the potential growth of AM to be a genuine competitor against existing conventional manufacturing technologies is the limited accuracy and process uncertainty that need addressing to improve AM predictability and precision.

This is especially true for powder bed techniques such as SLM, where the as-built quality of produced parts does not satisfy current manufacturing standards and tolerances. In particular, the SLM process faces several challenges such as the shrinkage and distortion due to the buildup of residual stresses, as well as dross formations [3].

A number of research studies have attempted to improve the precision of the SLM process. For instance, the effect of the scanning strategy on distortions and residual stresses have been examined [4]. Different methods have been developed to model the SLM process to enable the prediction and compensation for distortions [5].

Looking at the literature, although there have been noticeable reported studies on the influence of the process conditions of the SLM on the

accuracy of the generated parts, only few attempts were made to optimize the process [6]. Particularly to identify the proper processing window and optimal process parameters that would enable the production of highly precise products with tight tolerances and high quality. However, this imposes a systematic experimental study to comprehensively acquire the effect of the process parameters on precision matters such as dimensional accuracy, warpage and deflection.

In this context, the aim of the present research work is to experimentally investigate and correlate the effects of different build parameters on the dimensional accuracy of SLM, especially parts containing different overhang angles.

EXPERIMENTS

Test Piece

Separate test pieces containing different angles of overhangs (45°, 35° and 25°) were designed to enable the testing of the dimensional accuracy and they were built with a layer thickness of 60 μm . The test pieces and their dimensions can be seen in Figure. 1.

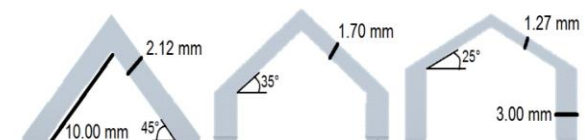


FIGURE 1. Front view of test pieces

Build Parameters

The down-facing area of an overhang is especially susceptible to deformations and defect

formation such as dross due to overheating of loose powder, therefore this down-facing area is the subject of the present research work. The most significant process parameters (laser power, scan speed and scan spacing) [6] were varied and applied to examine their effects on the down-facing area, where a hexagonal cell scanning strategy was applied. A depiction of the down-facing area can be seen in Figure.2. The remainder of the part (middle area) were built using 3D Systems recommended parameters for a 60 μm layer thickness.

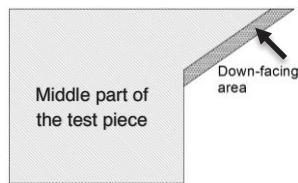


FIGURE 2. Depiction of the down-facing area

Design of Experiment

The chosen parameters are seen in Table.1.

TABLE 1. Selected parameters and their levels

Testpiece	Laser power	Scan speed	Scan spacing
1	90	465	60
2	90	465	90
3	90	1235	60
4	90	1235	90
5	210	465	60
6	210	465	90
7	210	1235	60
8	210	1235	90
9	50	850	75
10	250	850	75

Additive Manufacturing Tests

The test pieces were pre-processed in the 3DXpert™ software and the production was implemented in a 3D Systems ProX® DMP 320 and using LaserForm Ti gr23 (A) powder. As common practice, the test pieces were heat-treated before removal from the build plate to minimize any deformations and warpage after printing during base plate removal. Three built pieces, exemplifying the three different test angles can be seen in Figure.3.



FIGURE 3. Built test pieces after removal from build plate

Measurement and Evaluation

An optical microscope was used to take high definition pictures of the test pieces in order to evaluate the dimensional accuracy. The images were stitched in order to generate one complete image for each sample that can then be used for the evaluation. An example of one of the stitched test pieces can be seen in Figure 4.

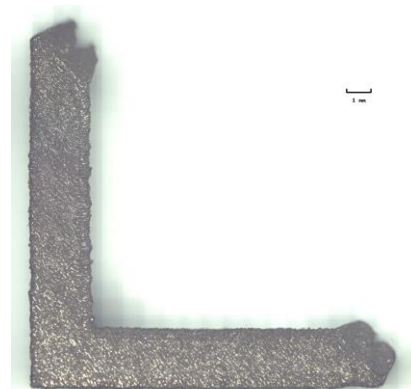


FIGURE 4. Stitched image of a 45° test piece

Since the down-facing area is being investigated, the thickness was chosen as the quality to be investigated as it is directly affected by the process parameters used to print the down-facing surface.

Measurement was done using the MATLAB image processing toolbox. The process of the measurement is as follows. First, the cross section of the as-build sample were scanned using an optical microscope as seen in Fig. 5a, to obtain as clear a definition as possible of the edges representing the boundaries of the part to be characterized. Second, the Matlab image processing software was employed to process the captured pictures and convert them into black and white images using a thresholding technique, as depicted in Fig. 5b. Subsequently, an edge detection technique was applied to define the segment of the part where its thickness will be evaluated. By conducting this segmentation, a matrix of points (X_i , Y_i , 0 or 1) is generated, where X_i and Y_i are the coordinates of each pixel and

the third binary number gives information whether this point belongs to the segment of the part to be measured or not, Fig. 5c. Finally, this data matrix is read to calculate the thickness of the part at different heights as can be seen in Fig. 5d.

The thickness measurement values for all test pieces were then analyzed to determine the error. Which then made it possible to calculate the error percentage. Minimizing the error percentage would directly improve the as-built dimensional accuracy, therefore it is the parameter chosen for optimization in the work reported in this paper.

In this research, the analysis of the thickness of the as-built part was restricted to the thickness close to the edge, however, in future work this will be extended to consider part thicknesses at different positions over the as-build parts. Also, mechanical measurement using caliper or another measurement technique will be undertaken which may give a more 'bulk' result, that can give information on the local cross formations.

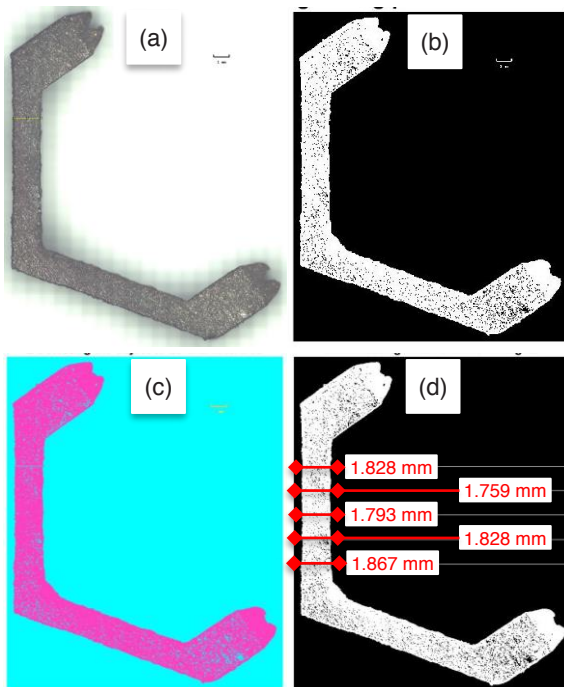


FIGURE 5. Image processing-based measurement techniques using MATLAB (a) optical micrograph of the part to be characterized, (b) black and white conversion of the original image using predefined threshold, (c) edge detection of the part, and (d) thickness measurements at different heights

The measured errors, error percentages and the standard deviation of the measured thickness values of the test pieces with 35° and 45° overhangs are presented in table 2. The comparisons between two process parameters for the 35° and 45° down-facing surfaces are presented in the following section. The following graphs were made by averaging the error percentages in order to obtain the plot points for the two process parameters. Only two parameters are compared at a time. Future work will see all parameters being considered during the multi objective optimization. Results presented herein are for the 35° and 45° down-facing surfaces.

TABLE 2. Error and error percentages of test pieces

No	Error for 35°			Error for 45°		
	mm	%	Std. deviation	mm	%	Std. deviation
1	0.20	11.99	0.05	NA	NA	NA
2	0.11	6.34	0.02	0.19	9.00	0.05
3	0.10	5.58	0.09	0.07	3.05	0.04
4	-0.07	-3.85	0.07	0.26	12.40	0.03
5	0.77	45.17	0.04	0.39	18.56	0.03
6	0.70	41.03	0.04	0.56	26.42	0.02
7	0.35	20.29	0.06	0.26	12.40	0.02
8	0.27	15.76	0.04	0.27	12.83	0.06
9	-0.09	-4.98	0.08	-0.03	-1.41	0.05
10	0.51	29.71	0.04	0.35	16.65	0.05

RESULTS

Effect of Laser power and Scan speed

Figure 6 presents the effect of laser power and scan speed on the obtainable error percentage as an indicator of the dimensional inaccuracies. Error percentages are seen to be higher at the higher power value of 210W and decrease in error percentage as it can be seen at a high scan speed. At the laser power of 90W both 35° and 45° down-facing surfaces show very similar error percentages at a low scan speed. However, at a higher scan speed the 35° surface shows a more significant decrease in error percentage whereas the difference is minimal for the 45° overhang at the same speed.

Table 3 depicts the average standard deviations for the test pieces at the measured power and scanning speed. The results indicate that for the 35° overhangs the slower speed of 465mm/s produces a more uniform part than the high speed resulting in lower standard deviations at

both level of laser power. While for the 45° the relationship differs as at the lower power value, standard deviation decreases while increasing speed and for the higher power of 210W the standard deviation increases while increasing speed.

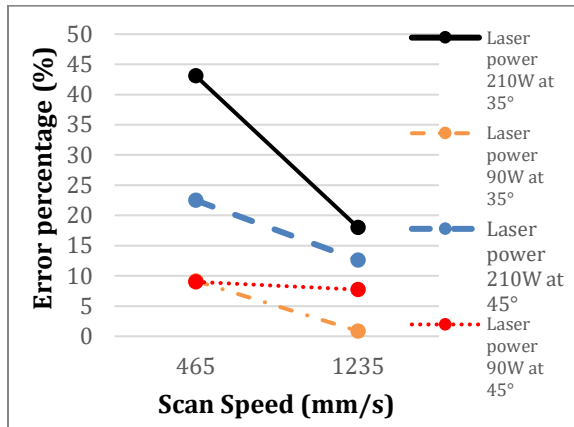


FIGURE 6. Relationship between laser power and scan speed

TABLE 3. Standard deviations

Overhang angle	laser power (W)	Std. deviation at 465 mm/s (mm)	Std. deviation at 1235 mm/s (mm)
35°	90	0.035	0.083
	210	0.039	0.051
45°	90	0.046	0.033
	210	0.025	0.038

Effect of Laser power and Scan spacing

When comparing laser power and scan spacing, consistent with the previous table, the error percentage is always seen to be higher for the test pieces printed with the higher power of 210 W, as seen in figure 7. However, the influence of increasing the scan spacing is seen to be different between the 35° and 45° test pieces. The error percentage decreases for the 35° surface while increasing the scan spacing seems to increase error for the 45° samples.

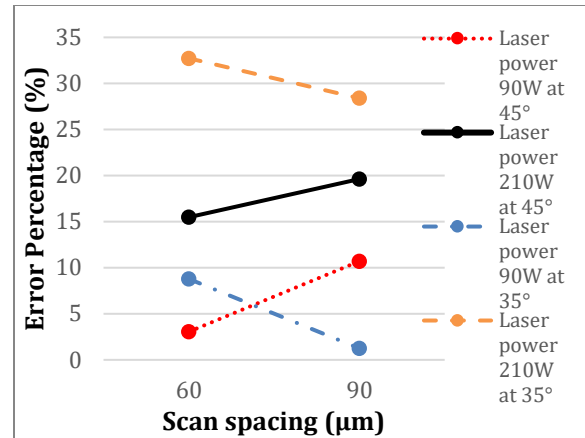


FIGURE 7. Relationship between laser power and scan spacing

Table 5 depicts the average standard deviations at the measured laser power and scan spacing. The results indicate that at the 35° overhang the standard deviation is lower at the 90μm than at the 60μm scan spacing. While for the 45° down-facing surface, at 90W, the standard deviation only shows a small increase at the 90μm scan spacing. While at the 210W, the standard deviation shows a larger increase at the 90μm scan spacing from the 60μm. While for both angles, at the 60μm scan spacing the standard deviation is consistently lower for the higher power.

TABLE 4. Standard deviations

Overhang angle	laser power (W)	Std. deviation at 60μm (mm)	Std. deviation at 90μm (mm)
35°	90	0.071	0.048
	210	0.047	0.042
45°	90	0.036	0.038
	210	0.025	0.038

Effect of Scan speed and Scan spacing

Observations from figure 8, while comparing scan speed and scan spacing show that the varying of these two parameters have different effects on the accuracy depending on the angle of the overhang. For a 35° overhang, the low speed and low scan spacing has a large error but the error reduces drastically when the scan spacing is increased. Though the reduction is also present for the high-speed built 35° surface, the degree of reduction is lesser. The 45° surface shows a small decrease when increasing scan spacing but the error is reduced even more for a higher speed build. These results indicate that the interaction

effect of scan spacing and scan speed have different intensities at different angles.

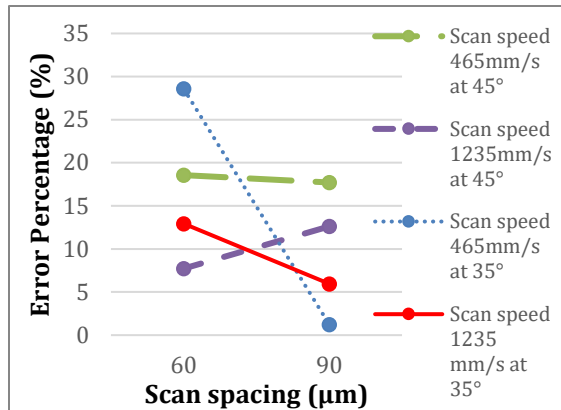


FIGURE 8. Relationship between scan speed and scan spacing

Table 6 depicts the average standard deviations for the measured scan speed and scan spacing. For the 35° angle, the 90μm scan spacing showed lower deviations than the 60μm while the 1235 mm/s scan speed showed higher deviations than the 465mm/s scan speed. While for the 45°, at 465 mm/s, the higher scan spacing only shows a small increase in standard deviation. While the difference in standard deviation is higher at the higher speed.

TABLE 5. Standard deviations

Overhang angle	Scan speed (mm/s)	Std. deviation at 60μm (mm)	Std. deviation at 90μm (mm)
35°	465	0.041	0.032
	1235	0.077	0.057
45°	465	0.031	0.032
	1235	0.027	0.043

DISCUSSIONS

First results show that one of the dominant effects affecting the dimensional accuracy is the laser power. Higher laser powers consistently showed high values of error percentage. This can be explained intuitively, as a higher energy absorption by the powder leads to the formation of larger melt pools. This coupled with the presence of only loose powder below the melt pool leads to an increased presence of partially melted powder on the surface of the overhang, leading to high dimensional inaccuracies.

45° down-facing surfaces generally exhibit self-supporting behavior to an extent. Therefore, to a

certain degree they are able to dissipate heat into the build platform. However due to a larger amount of loose powder below the 35° test pieces, the heat does not escape, as a result an overheated zone where more powder is melted causing more deformation and dross formation. This can be seen as the 35° overhangs consistently showed greater error percentages than the 45° overhangs.

One thing to keep in mind is that large melt pools generally have a greater wettability and can therefore easily fuse together with adjacent melt pools, which could cause the formation of large uniform dross. This kind of dross can manifest as smooth flat surfaces that appear to have good surface quality. Therefore, the study of dimensional accuracy must be coupled together with other surface profile studies such as the surface roughness.

The effect of changing the scan spacing is interesting as it has a different effect depending on the angle of the overhang. For the 45°, at both the high and low laser power, increasing the scan spacing led to larger error percentages, while the error percentages decreased for the 35° overhang. Moreover, for the 35° surfaces, built with a low scan speed, increasing the scan spacing showed a drastic decrease in the error percentage, while the effect was not as pronounced for the parts built with a higher scan speed. On the other hand, for the 45° test piece, the low speed sample showed a miniscule decrease in error percentage and the high-speed part actually saw an increase in error percentage. Therefore, the effect of scan spacing is also geometry dependent.

Conducting an investigation into parameters such as line energy can give insight into the size of the melt pools formed, leading to a better understanding of the scan spacing parameter, which allows us to learn more about the optimum overlap between melt pools and as a result will enable better decision making on optimum scanning space.

Dross formation can cause local variations on the dimensions of down-facing surfaces thereby affecting the thickness. In this case, investigating the standard deviations gives an idea on the uniformity of a surface and therefore information on the stability/instability of the process can be procured. Tables 4, 5 and 6 depict the process interactions that show the variations in thickness

measurements. Thereby giving an idea on the combinations that give rise to unstable processes. This information is valuable while conducting an optimization study where the development of a precision process is the goal.

Repeatedly the SLM process has shown that apart from its non-linearity, there exist complex interactions between parameters. In addition, uncertainties, such as the effect of middle parameters on the down-facing surface quality, exist. This adds to its complexity and unpredictability, making it a prime candidate for process modelling and optimization.

CONCLUSIONS

A beginning into the process modelling and optimization of the SLM process is shown in this paper. The first process of data acquisition is currently underway with some initial results and discussions presented herein.

1. Laser power is a dominant factor and further work must focus on including the effect of factors such as normalized enthalpy on the obtainable quality of the as-build part.
2. Higher laser power consistently showed higher values of error percentages.
3. 35° down-facing surfaces consistently showed higher error percentages than the 45° surfaces as expected. This is due to ability of 45° overhangs to provide a degree of self-support and therefore possesses a better ability to dissipate heat into the build platform.
4. The effect of scan spacing is also geometry dependent and factors such as line energy must be investigated for a better understanding.
5. The dimensional accuracy study, coupled with other surface quality studies such as roughness is required for a true understanding of the process.
6. Finally, including information on the variation of data points is important for the process optimization of the SLM process when precision is the goal.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] K. Brans, "3D Printing, A Maturing Technology", IFAC Proc., 2013; 46; 468-472.
- [2] N. Guo, Leu Ming C, "Additive manufacturing: technology, applications and research needs", Fron. of Mech. Eng., 2013; 8; 215-243.
- [3] Wang Di, Mai Shuzhen, Xiao Dongming, Yang Yongqiang, "Surface quality of the curved overhanging structure manufactured from 316-L stainless steel by SLM", The Int. Jou. Of Adv. Manu. Tech., 86; 781-792
- [4] Stacey D. Bagg, Lindsay M. Sochalski-Kolbus, Jeffrey R. Bunn, "The effect of laser scan strategy on distortion and residual stresses if arches made with Selective Laser Melting", ASPE Summer topical meeting 2016, Raleigh, NC, United States.
- [5] Shukri Afazov, Anestacy Okioga, Adam Holloway, Willem Denmark, Andrew Triantaphyllou, Sean-Anthony Smith, Liam Bradley-Smith, "A methodology for precision additive manufacturing through compensation" Prec. Eng, 2017;50;269-274.
- [6] R. Mertens, K. Kempen, S. Clijsters, J.-P. Kruth, "Production of AlSi10Mg parts with downfacing areas by Selective Laser Melting", 6th PMI conf. 2014, Guimarães, Portugal.

Computer vision for focus calibration of photo-polymerization systems

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INTRODUCTION

Photopolymerization by mask projection allow for rapid construction of extremely detailed and intricate objects, such as hearing aids. The Technical University of Denmark has long had an interest in applying computer vision systems to additive manufacturing systems to increase quality. To obtain the optimal quality for photopolymerization systems, it is paramount that the focal plane is exactly at the build plane. Manually finding the position with optimal focus is an arduous and time-consuming task. Previous attempts at implementing an automatic procedure for finding the optimum focus has failed [1].

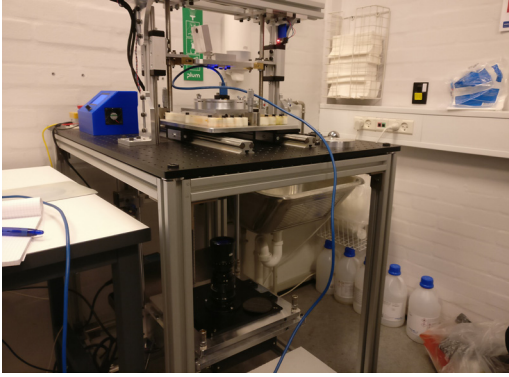


Figure 1: The mask projection based photopolymerisation system at DTU Dept. of Mechanical Engineering. The auto-focus solution is performed by placing the Blackfly S camera in a mount atop the glass-bottom of the vat.

In this paper we present an autofocusing solution for mask projection based photopolymerisation systems (MPPSs), with ease-of-use equivalent to the autofocus known from an ordinary DSLR-camera. The autofocus solution has been implemented and tested on the experimental MPPS (Figure 1) at Technical University of Denmark, Department of Mechanical Engineering using a PointGrey Blackfly S BFS-U3-51S5M-C industrial CCD-camera, no lens and pixel size of $3.45\mu\text{m}$. The MPPS is built using a Visitech Luxbeam Rapid System projector of LRS-WQ-HY, with a micromirror size of $7.5\mu\text{m}$ and depth-of-focus range of $\pm 50\mu\text{m}$ for the 1.0 magnification filter and $\pm 200\mu\text{m}$ for the 2.0 magnification filter [2], [3]. The lateral movement of the projector is designed with a motorized projector mount to have a minimum step size of $1.56\mu\text{m}$. By projecting an image from the projector up onto the glass plate where the camera is mounted and moving the projector laterally, we are able to implement autofocus. Our autofocus solution allows researchers faster and easier access to building on the MPPS, requiring no training in using calibration software or printer operating procedure outside the standard.

METHOD

The autofocus algorithm is built using a multi-scale global search algorithm with a local curve fitting approach based on a carefully chosen focus-measure. Deciding on which focus measure to use is a non-trivial issue and we refer the reader to [4] and [5] for an in depth study of a selection of focus measures. In our specific case on the MPPS we have found that Laplacian- and Haar-transformation-based focus-measures perform the best. The focus measure used in the current solution is based on Haar Wavelets and is calculated as shown in Equation 1, with $n = 2$.

$$F_{Haar,2^n} = \sum_{i=1}^N \sum_{j=1}^M \left[|\mathcal{V}_n(i, j)| + |\mathcal{H}_n(i, j)| \right]^2, \quad (1)$$

where $\mathcal{V}_n, \mathcal{H}_n$ are resp. the vertical and horizontal differences from n iterations of the Haar-transform, N, M are the dimensions of each these resulting images.

The search section of the auto-focus algorithm is a multi-scale global search combined with curve fitting, as presented in [6]. This algorithm requires a starting and end point of our search-interval, an initial step-size and a desired threshold defining how accurate we want our result from the search to be.

One could choose to use the entire accessible range of 325mm as the initial search interval with a coarse step-size, but the range where the CCD can capture actual data and not just noise is only about 10mm wide. Starting our algorithm on the entire range with too coarse a step size would, in worst-case scenario, result in not capturing any data in the usable range and hence the algorithm would only be dealing with input that is almost purely noise. Therefore we recommend that the initial search range is set to the interval in which some parts of the pattern is actually visible along with a step-size at around 1mm .

The starting position is denoted $R_0^t \geq 0$, the end position R_n^t , assuming $R_0^t < R_n^t, \forall t$ and the initial step-size S_0 . A number of images in the initial search interval are acquired, the focus measure at each step is evaluated and the position of the maximum focus in the interval is denoted FM_{max}^t .

Afterwards the distance from FM_{max}^t to R_0^t and R_n^t are found and the maximum distance is denoted D_t , i.e. $D_t = \max(|FM_{max}^t - R_0^t|, |FM_{max}^t - R_n^t|)$. The maximum distance, D_t is used to update the search interval and step-size. The new range is updated by $R_0^{t+1} = FM_{max}^t - \frac{D_t}{2}$, $R_n^{t+1} = FM_{max}^t + \frac{D_t}{2}$. The updated step-size is $S_{t+1} = \frac{D_t}{D_{t-1}} S_t$.

This is repeated until the distance between the current optimal focus position and the one in the previous step goes below a certain threshold. To minimize noise and improve accuracy, the maximum of a second order polynomial fitted to the data at a small range around the found optimal position, is chosen as the optimal focus.

This approach allows us to achieve high accuracy quickly. As an alternative we could use a global search over the visible range at the minimum step size at $1.56\mu\text{m}$, however this would require around $10/0.00156 \approx 6400$ steps. Assuming each step takes around 1 second this would take more than a 100 minutes. For comparison our solution with the proposed algorithm takes approximately 4 minutes to find the position of the optimal focus.

VALIDATION

A challenge in the implementation of an autofocus solution for a mask projection based photopolymerization system, is the fact that the depth-of-focus for these projectors is very low, especially when equipped with the short focal length 1.0-magnification lenses. Once we are out of this range, the noise level increases drastically, until there is no discernible signal left. As such, if the initial sweep is performed such that it misses the narrow band of actual signal, it breaks down completely. We propose two solutions for this problem, dependent on whether there is prior knowledge of where the in-focus position is: if no prior knowledge, a much more fine-grained sweep is performed. If prior knowledge, it is then only a small area around the presumed in-focus position is searched.

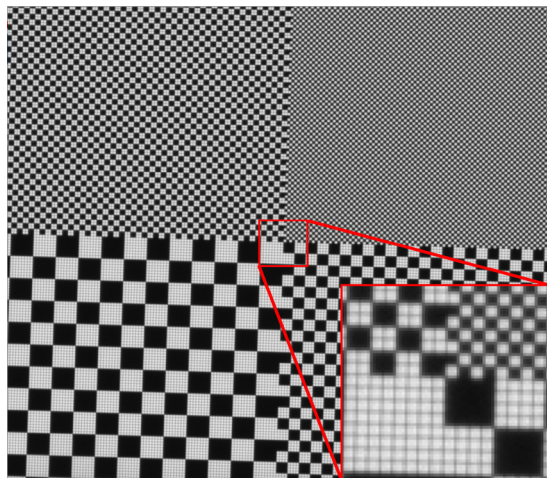


Figure 2: An in-focus view of the checkerboard calibration-mesh taken at the detected point of optimal focus, corresponding to the peak of Figure 3. Each tiny square in the top right corner is the projection from one micromirror.

In validating whether the found optimal point of focus is actually the optimum, we need to inspect the calibration mesh as it appears at this position. By using a checkerboard calibration-mesh with the same resolution as the MPPS, determining the degree of

focus corresponds to evaluating how discernible each micromirror is from each other. In Figure 2 each micromirror can clearly be distinguished, thus making it clear that this position is very much in-focus.

RESULTS

By using the Haar-base focus measure as described in Equation 1, we found that we could reliably distinguish a clear maximal focus-value when performing sweeps, an example is shown in Figure 3. Applying our Haar focus measure together with our search algorithm consistently found optimal focus positions within a range of $\pm 150\mu\text{m}$ for the 2.0-magnification lens.

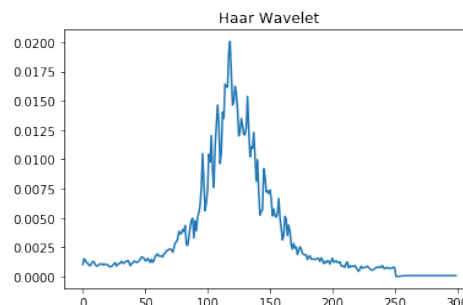


Figure 3: Haar-focus measure for 300 images taken with a stepsize of $10\mu\text{m}$, from 322mm to 325mm , normalized to have area of 1.

FUTURE WORK

In our current solution we compute the focus measure for an entire frame at a time, which under the assumption that the focal and the build plane are perfectly aligned, would be a completely fine approach. However, this might be a naive assumption since the building plate and vat are manually mounted prior to each print, which seems implausible to consistently accomplish with micrometer precision each time. To take this non-alignedness into account, we are currently trying to estimate a 3D model of the build plane using depth-from-defocus as shown in [7] and [8]. This would allow us to check the assumption and manually correct the leveling of the build plane if it is not perfectly aligned with the focal plane. In the long run the goal is to integrate the autofocus solution so it automatically runs and calibrates the focus before starting a build cycle.

CONCLUSION

Under optimal initial conditions we have succeeded in automating the tedious task of manually adjusting the focus on the DTU MPPS presented in [1]. The autofocus consistently finds an optimal focus in a range of $\pm 150\mu\text{m}$ for the 2.0-magnification lens, thus well within the depth-of-focus of $\pm 200\mu\text{m}$. The algorithm is not yet completely automated but we have shown that it is certainly possible to automate the task and we are working towards a fully automated solution.

References

- [1] F. W. Andersen, *Optimization of an experimental dlp platform by construction and process studies*, DTU Mechanical Engineering, 2018.
- [2] Visitech, "Specification and Data Sheet Projection Lens LRS-10 P/N 6501980,"
- [3] —, "Specification and Data Sheet Projection Lens LRS-20 P / N 6501990,"
- [4] S. Pertuz, D. Puig, and M. A. Garcia, "Analysis of focus measure operators for shape-from-focus," *Pattern Recognition*, vol. 46, no. 5, pp. 1415–1432, 2013, ISSN: 00313203. DOI: 10.1016/j.patcog.2012.11.011.
- [5] G. H. Zong, M. L. Sun, S. S. Bi, and D. Dong, "Research on wavelet based autofocus evaluation in micro-vision," *Chinese Journal of Aeronautics*, vol. 19, no. 3, pp. 239–246, 2006, ISSN: 10009361. DOI: 10.1016/S1000-9361(11)60351-8. [Online]. Available: [http://dx.doi.org/10.1016/S1000-9361\(11\)60351-8](http://dx.doi.org/10.1016/S1000-9361(11)60351-8).
- [6] S. Liu, M. Liu, and Z. Yang, "An image auto-focusing algorithm for industrial image measurement," *EURASIP Journal on Advances in Signal Processing*, 2016, ISSN: 1687-6180. DOI: 10.1186/s13634-016-0368-5. [Online]. Available: <http://dx.doi.org/10.1186/s13634-016-0368-5>.
- [7] S. N. Nayar, "Shape from Focus, Pattern Analysis and Machine Intelligence," *IEEE Transactions*, vol. 16, no. 8, pp. 824–831, 1994.
- [8] M. Moeller, M. Benning, C. Schönlieb, and D. Cremers, "Variational Depth from Focus Reconstruction," *IEEE Transactions on Image Processing*, vol. 24, no. 12, pp. 5369–5378, 2015, ISSN: 10577149. DOI: 10.1109/TIP.2015.2479469. arXiv: 1408.0173.

Intensity Mapping for Mask Projection based Photopolymerization

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Abstract

Currently, the industrial de-facto assumption for photopolymerization systems is that the ultraviolet light of the mask-projection is uniformly distributed. This paper presents a method for measuring this intensity field or distribution of this mask-projection. By measuring the light distribution, it is shown that the emitted light is not uniformly distributed and thus the current assumption is invalid. Furthermore, a methodology for obtaining a mask to compensate for the irregularities of the projected light, that will ensure an even and controlled exposure of the photopolymer, is presented. Accordingly, it is demonstrated that this mask compensates for such irregularities, making the light projection significantly more uniformly distributed.

1 Introduction

In order to obtain precision in additive manufacturing (AM), all aspects of the manufacturing process must be under control. This paper considers a bottom-up mask-projection based photopolymerization system, in which ultraviolet (UV) light initiates a cross-linking reaction which solidifies the photopolymer [1]. Currently, the de-facto industry assumption is that the projected UV light is uniformly distributed. This paper presents a new and novel method for measuring the distribution of the projected light with a machine vision camera with a CMOS sensor and shows that the assumption of uniformity is invalid. A method for obtaining a mask that compensates for the non-uniformity is presented, and it is shown that the suggested mask makes the distribution of the projected UV light significantly more uniform.

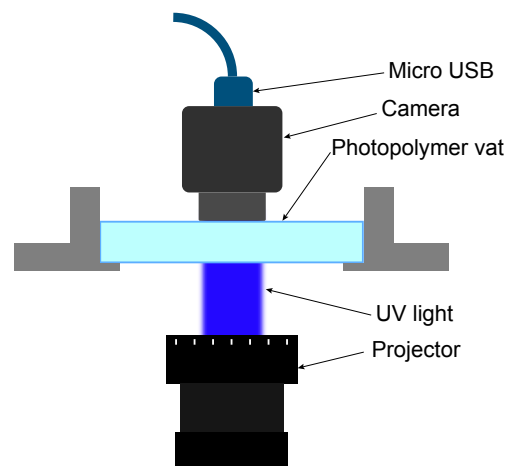


Figure 1: Representation of the image acquisition setup.

2 Method

This section will briefly describe the experimental setup. Then, the method for obtaining the intensity distribution is explained in two steps: First, how the measurements are collected. Second, how the measurements are stitched together to depict the entire area of the mask projection. The last part of the section explains how a mask for compensating for the irregularities of the projected light can be obtained.

1. Experimental setup

The vat-photopolymerization system used as a test platform was built by the Additive Manufacturing research group at the Technical University of Denmark. An area scan machine vision camera equipped with a CMOS sensor is placed on the resin vat, facing towards the projector system allowing the camera to image the light intensity field from the projector as seen in Figure 1.

However, the area of the projected light is significantly larger than the field of view of the camera. Therefore, multiple images have to be acquired from different positions to capture the entire area of projected light and subsequent stitched together. As such, this paper presents a novel method for keeping track of the position of the projected images while measuring the uniformity of the light intensity.

The photopolymerization system uses a Visitech Luxbeam Rapid System projector of LRS-WQ-HY, with a micromirror pitch of $7.54\mu\text{m}$ and depth-of-focus range of $\pm 50\mu\text{m}$ and $\pm 200\mu\text{m}$ for projection lenses with magnification factor of $1.0\times$ and $2.0\times$ respectively [5] [6]. The Blackfly S model BFS-U3-51S5M-C camera [2] was used for measuring the intensity of the projected light.

Only one channel of the Visitech Luxbeam Rapid System projector is used for projecting the UV light. Thus, the micro mirrors are constantly flickering between luminous and dark. In order to reduce this visible flickering, it is necessary to use a radiant flux of more than 0.38W . Furthermore, an exposure time of $33333\mu\text{s}$ (one projection cycle) is used. By using a whole number of full cycles, the integral of exposed light in this time period becomes independent of when the image is taken. In order to avoid overexposing the digital camera, a UV filter is placed such that only a small ratio of the projected light reaches the camera.

2. Measurement of the projected light

The image acquisition method was executed as follows. First a numerated checkerboard was projected onto the resin vat. An image of the checkerboard was taken in order to make it possible to identify the exact position of the camera. Then, a uniform white image was projected onto the vat and a picture was taken from the same position. By moving the camera and repeating this procedure, the position and intensity of each measurement are known and the whole area of projected light can be covered. Figure 2 shows the 20 measurements needed to cover the entire area of projected light. Each checkerboard image is associated with a corresponding intensity image taken from the same position.

3. Data processing

The following protocol was implemented in order to process the raw image data to a stitched contour map. First, all the images were cropped in order to remove the area outside the field of interest and to avoid overlap between the images. In order to reduce noise from the data each image was smoothed with a Gaussian kernel of 100.

Second, a normalization was performed since the aver-

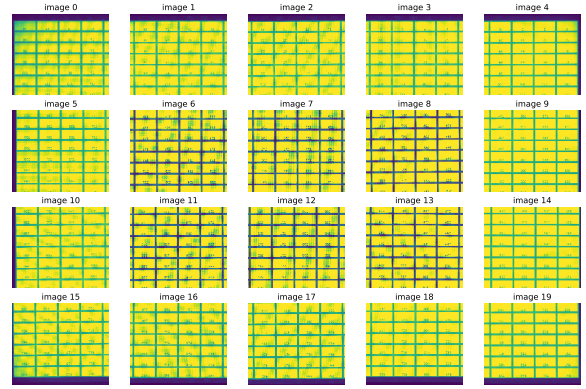


Figure 2: Images of the checkerboard covering the entire projection field.

age light intensity varied across the obtained intensity images. An iterative, relative normalization method is proposed and implemented such that each image is normalized relative to the borders of its neighbors. This normalization is performed iteratively, seeded at the center image (Figure 2, Image 12). In the first iteration Image 7, 13, 17 and 11 are normalized such that their border intensities match the borders of Image 12. Note that in the following iterations some images have to be normalized with respect to two images, e.g. in the second iteration, Image 8 has to be normalized with respect to both Image 7 and 13. This is done by constructing two weight matrices, $\mathbf{W}^1$ and $\mathbf{W}^2$, that weigh how much each border should normalize a given pixel. For the images in the top right and bottom left corner the weight matrices are given by

$$W_{i,j}^1 = \frac{h}{h+w}$$

$$W_{i,j}^2 = \frac{w}{h+w}$$

and for the images in the top left and bottom right corner the weights are given by

$$W_{i,j}^1 = \frac{h}{W+h-w}$$

$$W_{i,j}^2 = \frac{W-w}{W+h-w}$$

where h , w are the height and width of a given pixel respectively, and W is the width of the image. These weight matrices ensure that a pixel is normalized by a weighted sum of both the respective borders. A Python implementation of this iterative normalization method, together with a visual example on synthetic data can be found at: <https://github.com/FrederikWarburg/>

relative_normalization_methods#relative_normalization_methods

4. Compensation for non-uniformity

In order to compensate for the irregularities introduced by the non-uniformly distributed intensity projection, a simple and straightforward algorithm for obtaining a correction mask is presented.

Assuming linearity between the observed intensities and the projection, the mapping between the projected image and the observed image can be expressed as

$$p_{i,j}^{obs} = k_{i,j} p_{i,j}^{projected} \quad (1)$$

where $p_{i,j}^{obs}$ is the observed intensity for a given pixel, $p_{i,j}^{projected}$ is the projected pixel value and $k_{i,j}$ is a constant modelling the effect.

By projecting an uniform image onto the resin vat, $k_{i,j}$ can be found as the ratio between observed and projected pixel intensities. Thus, $k_{i,j}^{-1}$ can be estimated and be used to compensate for the non-uniform projection. $k_{i,j}^{-1}$ must be normalized such that each element remains within the range $[0, 1]$. If this is not done, one risk multiplying an image with a value greater than 1 which could lead to pixel values greater than 255 which is outside the range used to represent pixel intensities. The correction image $p_{i,j}^{corrected}$, which compensates for the non-uniform mapping, can be created as

$$p_{i,j}^{corrected} = \frac{1}{\max(k_{i,j}^{-1} p_{i,j}^{projected})} k_{i,j}^{-1} p_{i,j}^{projected} \quad (2)$$

Thus, applying $p_{i,j}^{corrected}$ instead of $p_{i,j}^{projected}$ will give the desired intensity and compensate for the irregularities in the projection.

3 Results

In this section, the mapping of the projected UV light is presented. The mapping shows that the projection is not uniformly distributed. Equation 2 is applied to compensate for this non-uniformity, and finally the performance of the suggested algorithm is evaluated.

1. Proof of non-uniform projection

By cropping the images and applying the iterative, relative normalization method it is possible to stitch the 20 images together without any visible stitches. Figure 3 shows an intensity map of the entire area of projected light and a contour plot of this intensity map.

From Figure 3, it becomes clear that the projected light is not uniformly distributed over the entire area

of the projection. The variance (V) and Christiansen's Uniformity Coefficients (CUC) are used to measure the uniformity.

$$V = 27.68$$

where 0 indicate uniformity.

$$CUC = 97.28$$

where 100 indicate uniformity.

It is seen that both these measurements that the light distribution is not uniform. Thus, it is shown that the assumption about uniformly distributed light in photopolymer systems is invalid.

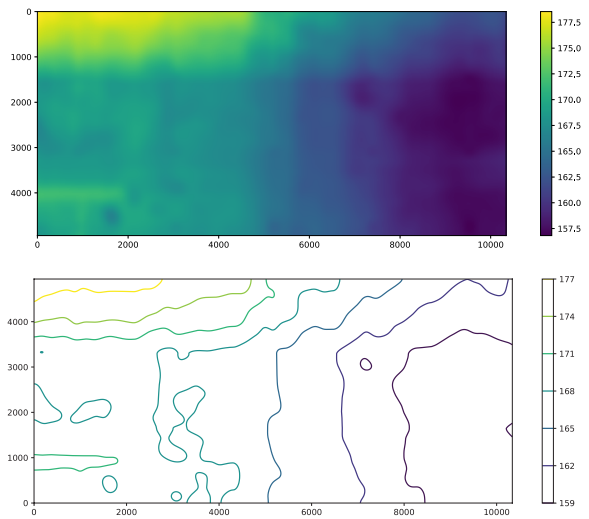


Figure 3: Intensity map of the entire area of projected light (top), and contour plot of the intensity map (bottom).

2. Compensation of non-uniform projection

Figure 3 shows that the projection is non-linear since the projection mapped an uniform, white image into a non uniform output. However, using this non uniform output enables estimation of a correction matrix $k_{i,j}$ and a correction image $p_{i,j}^{correction}$ using Equation 2. The correction of a white image is shown in Figure 4 together with a contour plot.

By projecting this correction image onto the resin vat, it is possible to compensate for the non-uniform mapping and thus obtain a significantly more uniform image. Figure 5 shows the results from applying the mask presented in Figure 4.

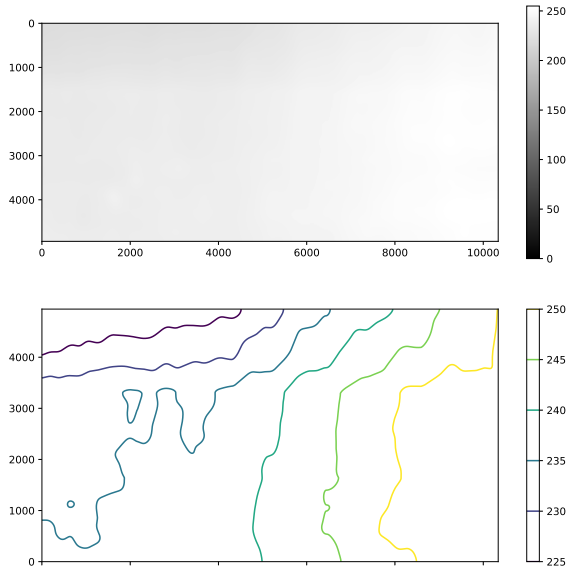


Figure 4: Normalized correction image for a white uniformly distributed image (up) and a contour plot of this normalized correction image (down).

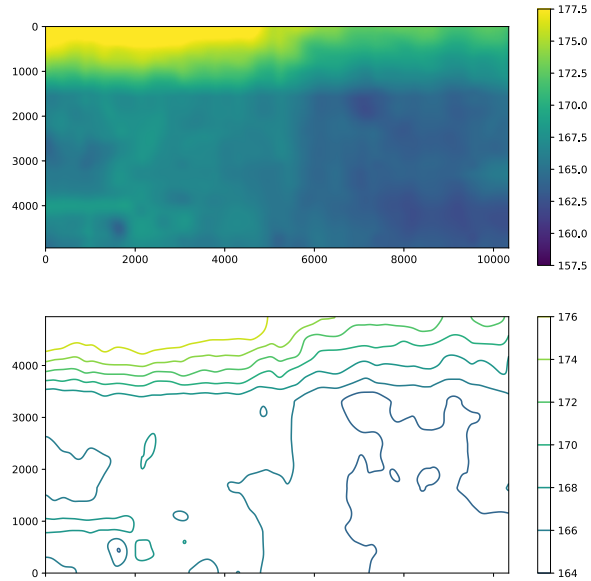


Figure 5: The results from applying the mask presented in Figure 4. Intensity map of the entire area of projected light (top), and contour plot of the intensity map (bottom).

Figure 5 shows that the strong trend from right to left observed in Figure 3 is compensated for. This makes the intensity distribution more uniform in the majority of the image, however it is seen that the image is still not uniformly distributed.

In order to compensate for measurement errors several measurements were made. Figure 6 shows the uniformity measures from an experiment where four white images and one correction image were projected onto the resin vat, following by the uniformity measurements. From this figure, it is seen that the correction image scores significantly better for both the uniformity measures. Thus, the correction is compensating for the irregular mapping performed by the projector by making the observed light intensities more uniformly distributed.

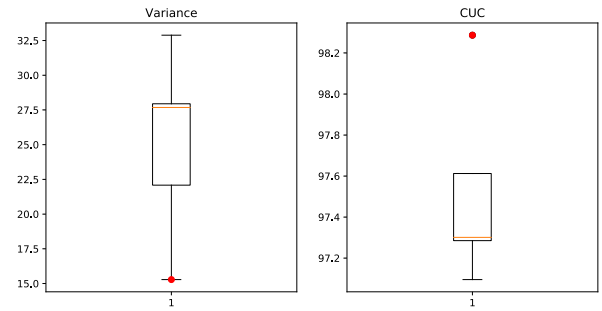


Figure 6: Boxplots showing the variance and CUC for 4 white image projections and 1 correction image. Correction image is the red dot.

4 Discussion & future work

The method described to measure the light intensity for the entire area of projection using a digital camera has shown that the projection is non-uniform and could be compensated for by using a correction matrix $k_{i,j}$. For the scope of this paper, it has only been investigated the uniformity of a pure white image. It would be of interest to repeat the experiment on images with lower pixel intensities.

In order to obtain more accurate measurements and correction matrices, a more stable camera holder should be made to ensure that the camera is moved in exactly equal steps to cover the projection on the resin vat and that the camera is held completely still when taking the set of images.

Furthermore, more sophisticated image stitching algorithms could be used to obtain the exact position of a measurement. This could be done by having a reference image im_{ref} containing many unique features, rather than a checkerboard which contains many similar (non-unique) features. Using the presented protocol, the position images could be mapped to the reference image using a homography [3]. This homography could rather easily be estimated by the feature correspondence

between the position image and reference image found using e.g. SIFT features [4]. This more sophisticated image stitching method would prevent overlapping between the sets of images, and could provide an elegant way of depicting missing spots of measurements. This could provide more accurate measurements and correction masks, while reducing the time spent on data gathering.

5 Conclusion

This paper has presented a method for measuring the UV intensity distribution of the entire area of the mask-projection for a photopolymerization system. A new and novel method for measuring the projected light intensities using a digital camera is presented and it is explained how an iterative, relative normalization method can be used for stitching the measurements together to depict the intensity distribution of the entire projection area. Based on this method, it is shown that the projected light is not uniformly distributed such as previously assumed for photopolymerization systems. Furthermore, a formula for obtaining a mask that compensates for the non-uniformity is presented. It is demonstrated that applying this mask compensates for the irregularities performed by the projector, making the mapping more uniformly distributed. Thus, applying this correction image will result in more accurate projections and higher precision in AM.

References

- [1] Frederik Winther Andersen. "Optimization of an Experimental DLP Platform by Construction and Process Studies". In: (2018).
- [2] FLIR. *BFS-U3-51S5 Datasheet*.
- [3] Serge Belongie David Kriegman. *Explanation of Homography Estimation*. 2007.
- [4] D. G. Lowe. "Distinctive Image Features from Scale-Invariant Keypoints". In: *IJCV* (2004).
- [5] Visitech. *Specification and Data Sheet Projection Lens LRS-10 P/N 6501980*.
- [6] Visitech. *Specification and Data Sheet Projection Lens LRS-20 P / N 6501990*.

ADDITIVE MANUFACTURING WITH ARC AND WIRE (3DMP®) – ACTUAL STATUS AND POTENTIALS OF A PROMISING TECHNOLOGY

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INSTRUCTIONS

In recent years additive manufacturing technologies have developed rapidly due to their capability of manufacturing near-net shape parts of complex geometry without dies or substantial machining, resulting in reductions of the lead-time, material waste and costs. Different 3D printing processes are extensively used to produce various kinds of parts including metal ones. Nevertheless, there are still significant obstacles in the production of large-volume components particularly in the efficiency of the process or material use. A major impediment in the application of additive manufacturing at industrial scale and its feasibility within the sustainable business cases is the limitation in component dimensions and low build-up rate of commonly used powder-based methods [1]. The wire and arc-based additive manufacturing is gaining interests due to its capability to produce near-net-shape parts of medium to high complexity at medium to large scale without the need for large, complex tooling using relatively simple and readily available welding equipment and control systems. The arc wire-based additive manufacturing technology, 3D-Metal Print (3DMP®), from GEFERTEC GmbH is a stable and economical process that provides new possibilities for producing large-volume components at industrial scale. High deposition rates, low material and equipment costs and good structural integrity makes the arc-wire-based manufacturing a potentially high beneficial replacement to machining out of solid billets or forging. For the 3DMP® process various kinds of weldable materials can be used. The material properties of the printed parts that have been validated in substantial tests and the possibilities of obtaining good mechanical properties and very high density of printed parts from 3DMP® process will be presented in depth showing high potential of arc and wire additive

manufacturing for applications in various industries.

STATE OF THE ART

Additive manufacturing defines a process that creates the shape of a workpiece by materially applying material. In contrast, for example, during cutting (such as milling or turning), the shape of the workpiece is created by material removal. This type of production offers new possibilities of component manufacturing. By applying material to create the geometry can be dispensed with conventional manufacturing processes in part or completely. [3]

The first industrial manufacturing additive manufacturing process was stereolithography in 1988. This process is based on a laser beam that cures layer by layer resin. [4]

The procedures, areas of responsibility and material diversity have expanded considerably since then. In addition to synthetic resins and ceramics, a wide variety of metal alloys can be processed additively and are used in aerospace, tool manufacture, in the automotive sector as well as in medicine and architecture. One possibility of the subdivision is the type of energy form, the energy transfer and the shape of the material to be processed. This occurs with metallic material on the one hand in the form of a laser beam (LBM), an electron beam (EBM) or arc (WAAM), as well as the raw materials used as raw material, e.g. in powder or wire form.

In addition to the technological differences, this classification can also be made from an economic point of view, since there are differences in production, acquisition and maintenance costs.

Apart from these criteria, the common methods can also be divided or differentiated in another way. However, this can only be practicably applied in the context of a detailed example and should only show the diversity of the technology

at this point. One way of obtaining an overview of the procedures is provided by the VDI Guideline 3405 and the standard DIN EN ISO / ASTM 52900.

3DMP® PROCESS CHAIN

The 3DMP® process is based on the fusion welding process with arc as an energy source and wire as filler material which is also referred as wire arc additive manufacturing (WAAM). In addition, 3DMP® integrates WAAM in a CNC machine and provides a fully functional CAM-software as well.

The arc generates the necessary temperatures for melting the wire and the base material. The inert gas separates the melt from the atmosphere and protects it from oxidation.



FIGURE 1. Aircraft part made of titanium (TiAl6V4), produced by 3DMP® process

The wire melted by the arc is applied path by Path and layer by layer. The solidified weld beads then form the component geometry. WAAM processes are characterized by very high build rates and a large variety of materials. [2].

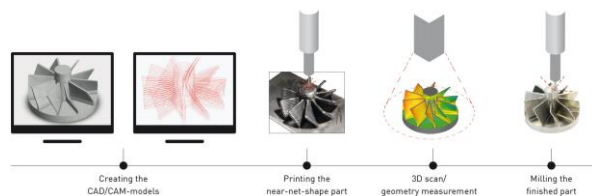


FIGURE 2. Process Chain for 3DMP® process

The welding paths are first applied to a substrate plate (similar material) and then successively welded over each other to build up height. With the appropriate machine configuration with a turn-tilt table, workpieces with overhangs and undercuts can be produced without support

structures. Consequently, the limits of this process, unlike powder bed processes, are no longer the dimensions of the powder bed (SLM) or necessary vacuum chambers (EBAM). The powders used in powder-based generative processes are also limited in variety and expensive to manufacture. All these factors can be excluded in WAAM based processes.

The variety in connection with a good availability of the welding filler wire makes the process flexible and opens a wide range of applications. It is also possible to process different metals in one process.

Nevertheless complexity, structure resolution and surface quality are limited, and a mechanical finishing is necessary in most cases

MATERIAL SPECTRUM AND PROPERTIES

Even with very high-priced or poorly machinable materials, generative production by means of electric arc and wire offers considerable cost advantages at an early stage compared to conventional production technologies.

In-depth investigations into the mechanical properties of materials qualified for the 3DMP® process show that they are comparable to those of conventionally prepared specimens.

Materials such as nickel-base alloys (for example Alloy 718) place increased demands on the process control in order to be able to meet the specific acceptance conditions, in particular with regard to hot cracks and mechanical-technological properties. The setting of the mechanical material properties is also possible for generatively produced components by means of downstream hot aging. This is done both anisothermally by the heat effect of the welding process on previously created material areas or by a heat aging at constant and component homogeneous temperature in the oven on various typical heat treatment cycles.

The yield strength for samples directly from the 400 MPa welded / as printed process is approximately equal to that of conventional blanks, e.g. Rods (as rolled) are known. As with these, the yield strength can be significantly increased up to about 1000 MPa by a targeted heat treatment. This also applies analogously to the tensile strength. Overall, however, it should be noted here that the test bodies have been produced using "conventional" wire as the starting material. Further developments regarding new alloy compositions of the wire feed materials with special adaptation for the 3DMP® process can be expected here

significant improvements in the mechanical-technological characteristics.



FIGURE 3. Microstructure of Alloy 718 blank: as welded (above) and after heat treatment (below).

As shown in Figure 4, the structure of Alloy 718 after the heat treatment differs significantly from the initial state. It can be seen that in the condition "as welded" no hot cracks or pores can be detected. The structure is predominantly dendritic. In the heat-treated state, a cast structure with precipitates can be identified, which are responsible for the increase in strength.

Even with low-cost and easily machinable alloys, such as aluminum alloys, advantages can be achieved at an early stage by the 3DMP® process, in particular with regard to throughput times. This is especially the case when prototypes and small series of cast components are to be replaced by generatively manufactured components. Here, the 3DMP® process can significantly shorten the process chain, and the paver can carry out all the steps "in house" and is no longer dependent on external suppliers and corresponding delivery times.

Especially with these materials, it is possible to achieve very good material properties through a targeted energy input and subsequent heat treatment adapted during 3D printing. Due to the good heat conduction a good thermal management can be built up. In a well-adjusted process, a pore-free structure and very good strength properties can be achieved. Thanks to the modern short arc technology, a large number of aluminum materials can be processed.

Noteworthy here is above all the almost pore-free construction of the generatively produced microstructure with mechanical-technological properties, some of which are significantly higher than the reference values of conventionally produced specimens made from rolled base materials.

Thus, the tensile strength is higher than the reference value and is independent of the construction direction, which speaks for a very homogeneous structure and a low influence of the HAZ on the component properties. This can be explained by the fact that due to the lower cooling rate and the repeated reheating the HAZ is changed in comparison to the normal joint welding. Further investigations are currently being carried out to evaluate the specific influences of critical component areas on the strength properties of generatively manufactured components.

CONSTRUCTIVE POTENTIAL

In addition to considerations on the material properties of printed samples, the design aspects of 3DMP®-generated components and structures are particularly important for the evaluation of their application potentials.



FIGURE 4. Variation of wall thickness and surface quality depending on process parameters.

By varying welding parameters such as feed rates and wire feed, it is, for example, possible to set wall thicknesses in a targeted manner. Depending on the material used, a continuous range from 2 mm to 8 mm can thus be reliably covered (Figure 4).

Furthermore, using the 3DMP® process in 3-axis mode with Cartesian axes (X, Y, Z) it is possible to produce overhangs in various shapes up to a maximum overhang angle of up to 45 ° without the use of support structures.

Larger overhangs and a combination of these can be created by using turn and tilt axes.

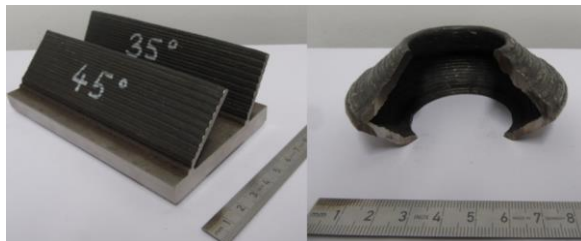


FIGURE 5. Generated by 3DMP® structures in 3-axis mode

Additive manufacturing processes are particularly advantageous over conventional processes when it comes to manufacturing components with integrated cooling channels. Particularly powder bed-based processes are suitable for the production of very filigree structures. The supporting effect of the already applied powder allows the production of cavities and channels. This must then be removed through a designated opening. By contrast, in the 3DMP® process, there is no other supporting material besides the applied weld metal. Also, additional support structures, as is customary in the FDM, not provided.

Investigations have shown that perpendicularly constructed channels, ie channels along the slicing direction, are easy to implement in terms of process technology. Diameters of at least 3 mm are readily achievable.

Due to the introduction mentioned missing support opportunities turn out channels with a circular cross-section, which run parallel to the layered structure, as unfavorable. A viable alternative in this case is to constructively adapt the channel cross-section so that each printed weld line along the opening has sufficient bearing surface through a track positioned thereunder.

Due to the given possibilities for the generation of freely selectable wall thicknesses in connection with complex structures, a potential

application for components in lightweight construction is conceivable.

The 3DMP® process currently works largely without support structures. It should be noted, however, that there must always be a basis for arc welding in which the next web can be welded. For this reason, freestanding areas require special construction strategies. In addition to the obvious solution to avoid such areas in general by the free areas, for later mechanical processing, be massively lined with material, this problem can be solved process technically.

CONCLUSION

The presented results show that additive manufacturing with electric arc and wire can already achieve very good mechanical-technological characteristics with a wide variety of materials. This makes this process predestined for extensive use in additive manufacturing, so that components can now be produced quickly and cost-effectively with the required properties using 3DMP®. In conjunction with the 3DMP®-CAM software and the GEFERTECarc machine concept, a large number of component geometries can be produced cost-efficiently.

Furthermore, considerations regarding the creative possibilities of the 3DMP® show that there is a large application potential in the market. In the context of the intensive further development of the process, a gradual further development of technological possibilities such as wire composition and process monitoring is also sought, so that in the future a further improvement of the mechanical and technological properties as well as design freedom is to be expected.

REFERENCES

- [1] Frazier, W. E., "Metal additive manufacturing: a review", In: Journal of Materials and Engineering Performance 23 (2014), p. 1917–1928
- [2] Martina, F., "Recent developments in large-scale wire+arc additive manufacturing", Additive Manufacturing in aerospace, ILA, Berlin, Germany, 2016.
- [3] Alfred Herbert Fritz und Günter Schulze. Fertigungstechnik. 10. Aufl. Springer-Verlag, Berlin Heidelberg, 2012.
- [4] Klocke. Fertigungsverfahren 5. Gießen, Pulvermetallurgie, Additive Manufacturing. 4. Aufl., Springer Vieweg, 2015.

CHARACTERIZATION OF ADDITIVELY MANUFACTURED METAL FLEXURE HINGES

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INTRODUCTION

The application of flexure hinges in precision engineering is widespread and has steadily increased in the past. Additive Manufacturing (AM) offers great design and manufacturing freedom for complex, functional integrated structures, such as flexure hinges. This opens up new opportunities for realizing complex motion. However, for long-term used AM hinges it is crucial to ensure fatigue strength. To achieve that goal it is essential to investigate their mechanical behaviour to ensure successful application.

METHODS

A simple design approach based on Howell et al. [1] and Raatz [2] is chosen for the analysis of the flexure hinge behaviour. For manufacturing the flexure hinge geometry the AM technology Laser Powder Bed Fusion (LPBF) is chosen using a modified laboratory machine based on the AconityMINI (Aconity3D, Germany) system technology (Beam diameter $75\text{ }\mu\text{m}$, layer thickness $20\text{ }\mu\text{m}$, scan speed 825 mm/s , hatch distance $60\text{ }\mu\text{m}$, laser power contour 125 W , laser power hatch 155 W) and stainless steel 316L (TLS Technik, Germany) powder material with a particle size between $10 - 40\text{ }\mu\text{m}$. Finite Element Analysis (FEA) Simulation is performed with ABAQUS V2017 (DASSAULT SYSTEMS, France) to evaluate the resulting inner von Mises stresses induced by a given swivel angle [3]. The material yield strength of 550 MPa is considered for determining the maximum swivel angle [4]. A fatigue test bench is used to perform mechanical fatigue tests of the AM flexure hinge with a frequency of 5 Hz [5]. The tested specimen are neither surface nor heat treated. Microscopic examination is performed on a Zeiss Axio Imager A2m and LEO 1455VP (Carl Zeiss AG, Germany).

RESULTS

Testing geometry and specimens

The specimens are build up in z-direction illustrated in FIGURE 1. After manufacturing the specimens are seperated from the substrate plate via wire-EDM.

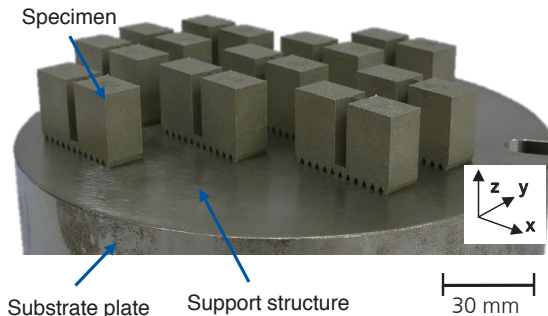


FIGURE 1. LPBF specimens positioned on the substrate plate before removal.

The testing geometry is defined as shown in FIGURE 2. Two rigid cuboids connected by a flexible rectangular beam form a simple corner-fillet flexure hinge. To avoid notching effects in the transition section radii are applied in between the rigid cuboids and the flexible beam. To reduce process time and material use the rigid parts of the geometry are hollowed. The beam length is limited by the fatigue test bench's dimensions and defined at 3.5 mm . For the size of the radii it is assumed that 0.5 mm is sufficient to avoid failure due to notching effects at the transition area. This assumption is verified in the fracture analysis.

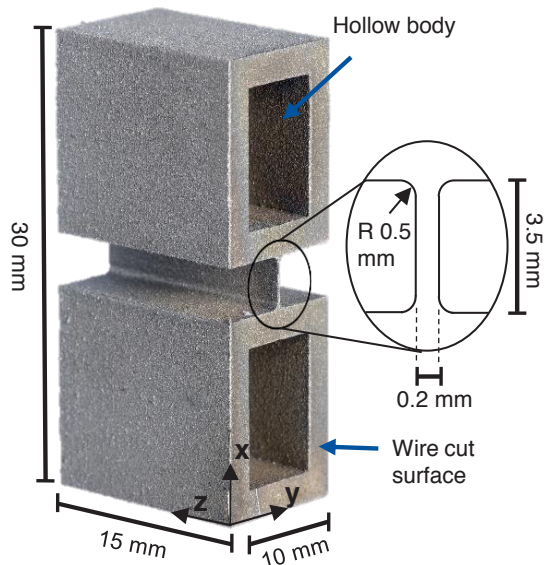


FIGURE 2. LPBF specimen after additive manufacture and severing from substrate plate.

Preliminary investigations to determine the minimal producible beam width are performed by producing specimens with three different target widths ($150\ \mu\text{m}$, $200\ \mu\text{m}$, $250\ \mu\text{m}$) using the same process parameters. Their cross-sections are examined on Zeiss Axio Imager A2m microscope as shown in FIGURE 3.

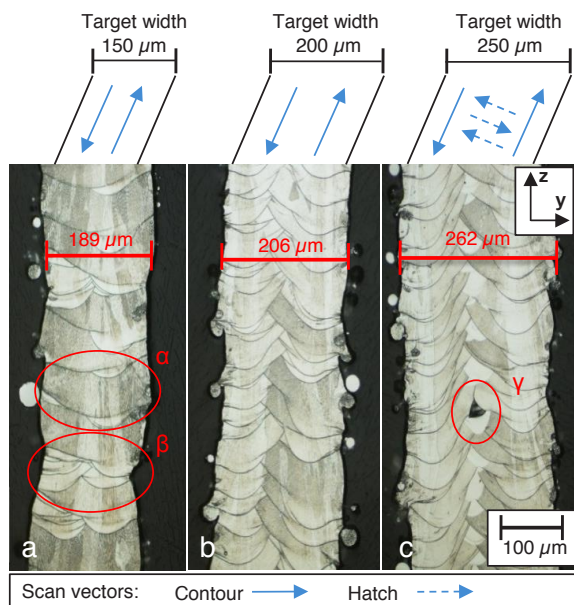


FIGURE 3. Comparison of cross sections showing LPBF produced beams with target widths $150\ \mu\text{m}$ (a), $200\ \mu\text{m}$ (b) and $250\ \mu\text{m}$ (c) as well as their related scan vectors

The microstructures are visualized by electrochemical etching with 5 % oxalic acid. In detail α of FIGURE 3 it can be seen that the melting traces of the two contour lines converge due to a small defined overlap area which therefore leads to a high energy intensity. As result the target width of $150\ \mu\text{m}$ is highly exceeded ($+39\ \mu\text{m}$). Detail β shows constriction due to less converged melting traces with a width closer to the target width. However, the constriction might result in higher notching effects. Detail γ highlights a pore resulting from an incorrect exposure of the short hatch vectors of $50\ \mu\text{m}$ length which are required to achieve the target width of $250\ \mu\text{m}$. Hence the short hatch vectors are a risk for the specimens density. The cross section with target width $200\ \mu\text{m}$ has no visible defects and the best dimensional precision ($+6\ \mu\text{m}$). The minimum replicable width of the flexible rectangular beam is therefore defined as $200\ \mu\text{m}$.

Simulation

A static FEA simulation is performed to quantify the internal stresses of the specimens during the fatigue test with defined boundary conditions as shown in FIGURE 4. The boundary condition in the simulation model equals the actual condition on the test bench in [5].

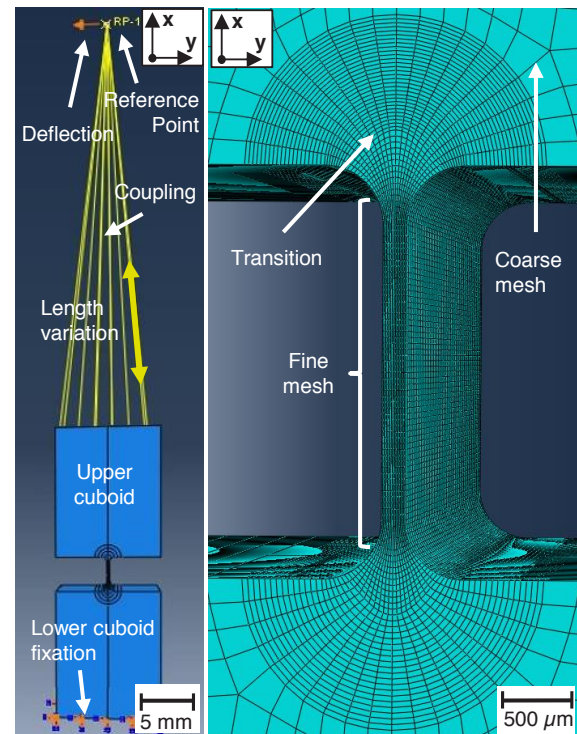


FIGURE 4. FEA simulation boundary conditions of the testing geometry

The lower cuboid is fixed and the upper cuboid is connected to a reference point by a coupling condition. To achieve the desired swivel angle the reference point is displaced in y-direction by a defined length. To avoid additional longitudinal stress during deflection the reference point can be displaced in the longitudinal direction of the coupling. A fine mesh with C3D8 elements is used for the flexible beam and the transitions. To reduce simulation effort the mesh is coarser for the cuboids which are assumed to be rigid.

As a result of the simulation, the inner von Mises stresses are distributed as shown in FIGURE 5. In the xz-direction, the maximum stresses appear in the lower area of the beam and expand to the top by shifting sideways. The distribution in xy-direction shows a linear progression starting in the middle of the flexible beam from the neutral fiber (0 MPa) up to a maximum at the side surface of 546 MPa and a resulting swivel angle value of 4.3 °. With the simulation model it is therefore possible to determine the maximum internal stresses at defined swivel angle values for the fatigue test.

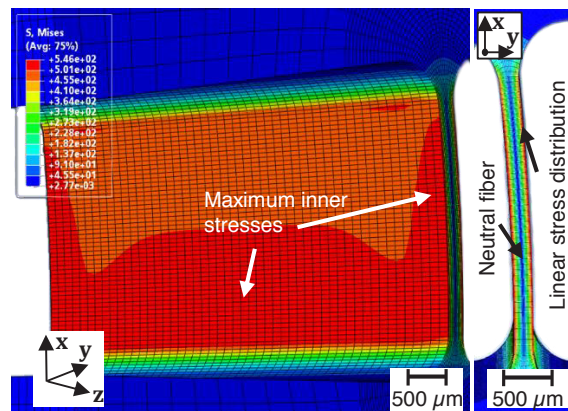


FIGURE 5. FEM Result showing the distribution of inner von Mises stresses in xz-direction (left) and xy-direction (right).

Testing Parameters

For the fatigue tests the specimens' geometrical dimensions are kept constant. Due to using different swivel angles the stresses can be changed precisely. Three different angles are tested to determine the fatigue strength of the specimens. The maximum angle is adapted to the yield strength of 550 MPa of stainless steel 316L, which can theoretically be achieved without plastic deformation. TABLE 1 shows the applied swivel angles with its predicted maximum inner stresses.

TABLE 1. Comparison of the tested specimens

Swivel angle [°]	Thickness beam [μm]	Predicted max. inner stress $\sigma_{P,max}$ [MPa]
4.3	204	557
4.3	200	546
4.3	198	541
3.0	209	397
3.0	200	381
3.0	195	372
1.8	203	232
1.8	199	228

Eight specimens are tested at defined parameters. Due to the statistical shape deviation of the LPBF process, the thickness of the specimens' flexible beam varies with a standard deviation of $\pm 4.3 \mu\text{m}$. This deviation is measured after production and reconsidered in FEA, which results in the predicted maximum inner stresses of TABLE 1.

Mechanical fatigue test

A fatigue test bench is used to investigate the fatigue strength behaviour of the specimens under the conditions shown in TABLE 1.

The results can be presented in a SN curve as shown in FIGURE 6. Fatigue strength is assumed at more than 10^7 load cycles which is equivalent to 23 days of testing at a frequency of 5 Hz.

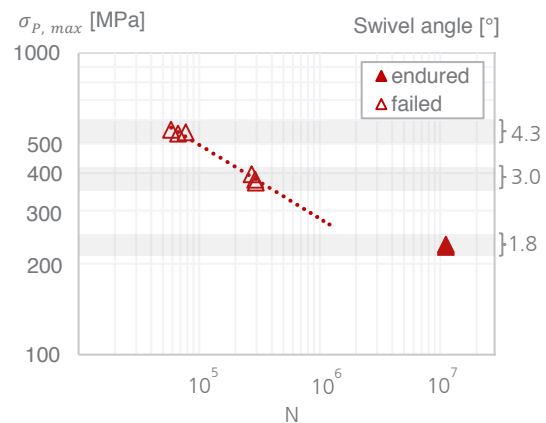


FIGURE 6. SN curve of the tested specimens.

For specimens tested with swivel angle 4.3 ° failure occur at 67.568 (± 9.498) load cycles. Specimens bended with 3.0 ° are neither fatigue endurable and failure occur at 286.743 (± 12.047) load cycles. Where as the two specimens tested with an angle of 1.8 ° endure the testing and withstand loadcycles greater than 10^7 . By drawing a linear line through the measurement points of failed specimens a assumption about fatigue strength for other stresses can be made.

To complete the SN curve and specify the assumption further tests with different swivel angles and their associated stresses are required.

Fracture Analysis

The fracture surface of the failed specimens indicates failure causes and occurred stresses. Furthermore it can be used to validate the simulated distribution of the inner stresses. In FIGURE 7 a fractured specimen tested with swivel angle of 4.3° is shown. The fracture appears noticeable closer to the bottom cuboid. This behavior occurs on all failed specimens. This implies higher stresses in this section and matches the simulation results shown in FIGURE 5. In the detailed section of FIGURE 7 it can be seen that the failure occurs above the radius. A fracture due to a radius selected too low can therefore be denied.

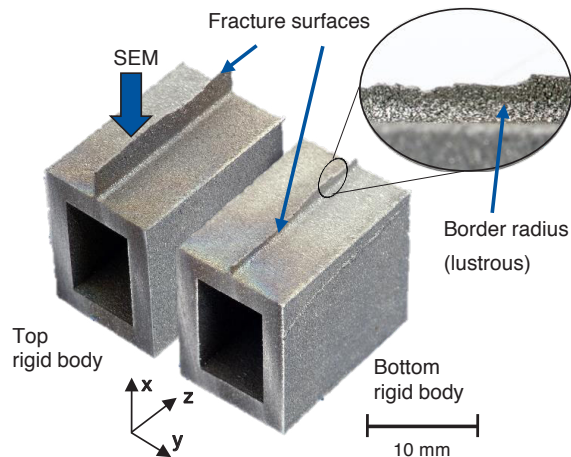


FIGURE 7. Fractured Specimen tested with a swivel angle of 4.3°

For microscopic examination a scanning electron microscope (SEM) is used. The results of this examination are shown in FIGURE 8.

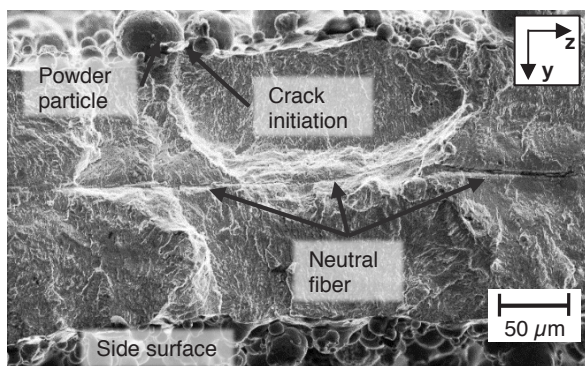


FIGURE 8. SEM picture of Fracture surface of specimen bended with 4.3°

The neutral fiber is clearly visible in the center of the flexible beam as a fracture line. Further fracture lines are vertically orientated to the neutral fiber and may be the result of cracks extending from the side surfaces to the center. The initiation of those cracks seem to be preferable at points where powder particles are attached. This could be the result of a notching effect due to the attached particles.

DISCUSSION & CONCLUSIONS

The presented approach shows that fatigue strength flexure hinges can be manufactured by LPBF. The mechanical tests and FEA results indicate that the stress limit of a flexure hinge is lower than the theoretical yield strength. High surface roughness and sintered powder particles presumably reduced the fatigue strength by local stress concentration and notching effects. Crack initiation can often be observed at attached powder particles. Therefore, an appropriate defined and reproducible surface treatment has to be considered to increase fatigue strength. The SN curve indicates that a corner load cycle value for fatigue strength behavior exists between the tested swivel angle values. However, more specimens have to be manufactured and tested to validate the SN curve progression.

REFERENCES

- [1] Howell L L. Compliant Mechanisms. John Wiley and Sons, Inc. New York: 2001
- [2] Raatz A. Stoffschlüssige Gelenke aus pseudo-elastischen Formgedächtnislegierungen in Pararellrobotern. Vulkan. 2015
- [3] Kimm M et al. Design of Flexible Implants for Preservation of Physiological Mobility Exploiting Additive Manufacturing. CAOS 2017. Aachen: 2017
- [4] Buelmann J, Merkt S. Scalability of the mechanical properties of selective laser melting produced micro-struts. Journal of Laser Applications 27, S29206. 2015
- [5] Schoenen, D et al. Development, design and application of a fatigue test bench for high precision flexure hinges. Proceedings of the ASME Design Engineering Technical Conference 2016 Vol.5. Charlotte: 2016

FATIGUE BEHAVIOR OF SURFACE TREATED TI-6AL-4V MADE VIA ELECTRON BEAM MELTING AS INPUT FOR A HYBRID PROCESS PLANNING SYSTEM

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INTRODUCTION

Inherent process inaccuracy and use of support structures often mean that metal additive manufacturing (AM) is incapable of producing parts with specified tolerances for industrial use. For this reason, additional post processing of the surfaces may be required. Through the integration of current AM and subtractive manufacturing (SM) systems, the Digital Additive and Subtractive Hybrid (DASH) process addresses these limitations. If the surface of the AM part being used in DASH more closely matches the final requirements, a substantial production savings can be achieved. Surface quality improvement can be achieved through mechanical or chemical treatments, however these processes can impact the fatigue performance and general machinability of the part. A comprehensive understanding of the fatigue behavior due to the effects of such surface modifications is important for various reasons within the DASH context as well as for the general application of AM in industry. The surface characteristics and fatigue behavior of as-built, chemically finished, and mechanically finished conditions were studied to begin development of a series of guidelines for designing and finishing of AM components.

DASH

While significant efforts have been made to improve the metal AM part as it comes out of the machine, there is far less work that has focused on addressing the production of legacy parts and one-of-a-kind parts by utilizing finishing on a critical feature-by-feature basis. The DASH process [1, 2] was developed to address this need by specifically focusing on issues regarding (1) the definition of features, (2) the utilization of raw material, (3) the localization of the as-built and mounted part for machining, and (4) the generation of toolpaths.

The DASH process, shown in Figure 1, begins with identification and tolerancing of critical features (i.e. holes, flats, mounting surfaces, etc.) within a part model based on user input. This information and part geometry is then analyzed to determine an ideal orientation for the addition of sacrificial support structures for machining purposes. With desired fixturing orientation, any machining allowance required to manufacture the critical features is added and the part is produced on any suitable AM machine. After this, the part is placed in a computer numerical controlled (CNC) machine where laser scanning is used to perform in-machine sensing which determines the shape and position of the as-built and as-mounted AM part. A small amount of artificial overgrowth is added to the point cloud generated during the laser scanning step to ensure full encompassment of the part model. This overgrown scan is used to compute offsets for AM error and fixturing error compensations. With the errors accounted for, toolpaths are automatically generated to machine the final geometry.

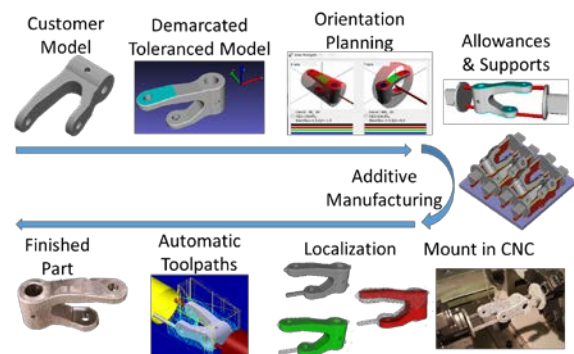


FIGURE 1. DASH process overview.

Features that are defined as critical are set as a priority in the DASH system, however non-critical surfaces are still important to the functionality of the component in its intended application. If the

surface finish of all surfaces on a part could be improved by traditional or non-traditional finishing methods, one could expect an improvement in fatigue performance and increased lifespan of the part itself. Additionally, this surface modification could also bring certain features into specification and mean that no additional machining is required through the DASH process. As alluded to, this improvement in non-critical features is ideal for many reasons, however machinability of critical features could negatively be impacted and the machining allowance requirements would be ambiguous. Thus, better understanding of the impacts of traditional and non-traditional surface conditioning methods is required.

EXPERIMENT

All one hundred four samples were manufactured from standard plasma atomized Arcam Ti-6Al-4V powder (45-105 μm) using an Arcam Q10plus electron beam melting (EBM) machine with standard Ti-6Al-4V build themes (software version 5.0.57). Samples were produced in the XZY and YZX orientations, as described in ISO/ASTM 52921-13, to preferentially orient any potential layer defects from the AM process during testing [3]. A 4mm spacing between individual samples was included to help thermally isolate individual parts and distribute heat across the build layers. This build layout allowed a total of fifty-two samples to be produced in a single build, meaning a total of two builds were required to produce all the samples. After manufacturing, samples were randomly assigned to each of the surface conditioning methods across both builds to reduce potential effects of sample location on the build plate.

Surface Treatments

Samples were assigned to one of seven surface treatment methods (Control, HIP-Control, RASP, SPEX, ChemEtch1, ChemEtch2, and Abrasive). Hot isostatic pressing (HIP) was performed on all samples except the as-built control group to match common industry practice to minimize the effects of any internal porosities. The HIP parameters were based on previously published work from Arcam AB [4].

Besides manual support removal, no additional processing was performed on the control group samples. In the HIP-Control group, only HIP was performed after manual support removal. Rotationally Accelerated Shot Peening (RASP) treatment described by [5] was performed on HIP samples for 8 minutes using 0.8 mm diameter

stainless steel balls and a rotational speed of 80 m/s. The SPEX ball-milling treatment was performed again on HIP samples for 120 minutes total duration using a SPEX 8000M Mixer Mill and 3.175 mm diameter stainless steel balls. Two types of chemical etching processes were performed on HIP samples (Chem Etch 1 and Chem Etch 2). Complete sample immersion in the etching solutions containing different percentages of hydrofluoric, nitric, and hydrochloric acids occurred for a maximum of 10 minutes before the samples were removed from the etchant and rinsed for 7 cycles. The abrasive treatment was performed using a Hybrid DECI Duo machine for a total treatment time of 4 minutes. With a 2-6 inch working distance, this process utilized an alumina based abrasive solution (52 grit particles) which was accelerated at the sample with 110 PSI.

Characterization

Analysis of the microstructure before and after HIP was performed via optical microscopy to determine the closure of voids and internal pores as well as to observe any changes to the samples' microstructure. Figure 2 shows the effect of the HIP treatment as compared to the as-built condition. It specifically shows the microstructure and defect population between the Control and HIP-Control samples. A closure and/or healing of the majority of the voids and defects occurred during HIP and there was only minor change in microstructure that was incurred. Because the minimization of internal stress concentration sites was a priority, any changes in microstructure were ignored.

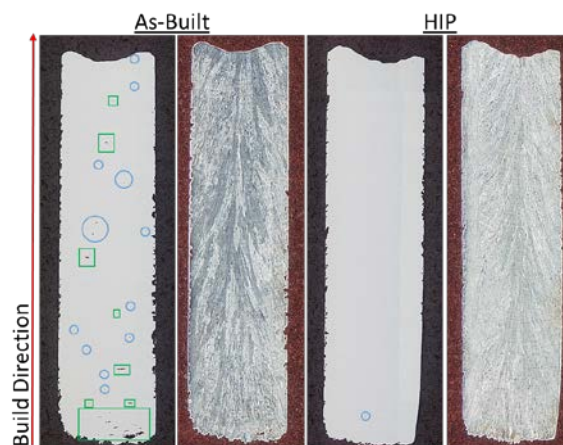


FIGURE 2. Comparison of microstructure and defect population. (Circles encompass point defects, Rectangles encompass layer defects)

Characterization of treated surfaces and fracture surfaces were done using a scanning electron microscope (SEM). The SEM images can be seen in Figure 3. As compared to the Control surface the surface treatments have drastically different appearances. Evidence of the compaction of surface particles can be seen in Figure 3b and 3d. This is shown in the regions of the partially compressed valleys from the original surface and the surrounding flat surfaces. While the spherical nature of the surface particles from the metal AM surface can be observed in Figure 3e, smoothing of these particles is clearly evident. The surface in Figure 3c is the most unique from the Control surface in Figure 3a and shows signs of particles being sheared from the surface. An energy-dispersive (EDS) detector incorporated into the SEM was used to determine the fundamental compositional information of the surface and ensure residual materials from surface treatments were not present in the SEM images.

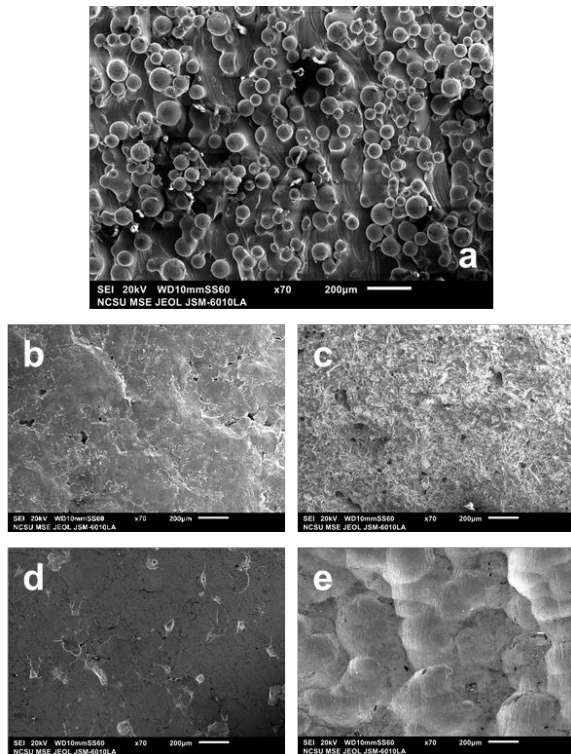


FIGURE 3. SEM surface comparison. a) As-built Control, b) RASP, c) Abrasive, d) SPEX, e) Chem Etch 2

Comparison of surface roughnesses of each treatment group were performed using the multi-synthesis tool on a HIROX KH-7700 digital

microscope (control and HIP-Control groups only) or a Dektak 150 Surface Profiler (all other treatments). The multi-synthesis tool was used to measure the control and HIP-Control groups because the vertical range of the Dektak was not sufficient for these samples. At least three different HIROX Ra measurements were collected across the sample surfaces in random diagonals and were averaged together to determine a Control sample Ra of 28 μm . An average Ra was calculated for two different directions, along (vertical) and across (horizontal) the build direction, from five measurements taken with the Dektak in each direction. The results from these measurements can be seen in Table 1. It is clear that all post treatments improved the surface roughness as opposed to the as-built control surface.

TABLE 1. Dektak measurement summary. (H indicates parallel to the build direction, V indicates perpendicular to the build direction)

Treatment	Avg. Ra (μm)	SD (μm)
H - SPEX	8.15	2.27
V - SPEX	8.07	2.29
H - Chem Etch 1	20.62	4.37
V - Chem Etch 1	18.51	2.26
H - Chem Etch 2	11.06	1.76
V - Chem Etch 2	10.91	0.96
H - Abrasive	8.27	1.50
V - Abrasive	8.96	1.76
H - RASP	14.16	1.49
V - RASP	16.27	2.30

Mechanical Testing

To test a sampling area of the surface, four-point flexure testing was conducted. This was done using a Testresources 910LX15 Servo Hydraulic Axial Fatigue Testing Machine with a 15 kN capacity in accordance with ASTM C1161-13, as seen in Figure 4. Braces were also included to prevent unwanted sample movement away from the load noses that might cause premature failure from excessive pinning. During these tests the load span-to-support span ratio was 1:2, and the test was automatically stopped when 1E6 cycles were performed or when failure occurred and the number of cycles were recorded.



FIGURE 4. Four-point flexure testing setup.

Static loading tests were carried out to confirm the UTS for AM Ti-6Al-4V gathered from literature to identify maximum loading from which testing loads were calculated (65%, 55%, and 45% of maximum load, which were 717 MPa, 607 MPa, and 496 MPa respectively). The preliminary results from these fatigue tests can be seen in Table 2.

TABLE 2. Preliminary fatigue results (average and standard deviation reported)

Treatment	45% UTS μ (σ)	55% UTS μ (σ)	65% UTS μ (σ)
Control	-	-	13,481 (2,829)
HIP-Control	47,451 (3,746)	17,328 (7,978)	13,060 (1,378)
RASP	313,169 (42,410)	78,382 (9,069)	43,328 (9,843)
SPEX	-	-	112,462 (10,076)
Chem Etch 1	-	-	44,768 (9,423)
Chem Etch 2	-	-	46,882 (10,755)
Abrasive	219,829 (127,334)	73,723 (41,374)	53,454 (34,698)

From these results no significant effects between the Control and HIP-Control are observed, which supports the hypothesis that surface effects dominate the mechanical testing. Additionally, the variability of the results after surface modification is dependent on the post treatment method itself as some treatments, like Abrasive, indicate an increase in variability.

CONCLUSIONS

As a result of this work it was determined that each of the post treatments produced unique surfaces that, in some cases, significantly

improve the fatigue behavior. Surface modification was also shown to improve the surface roughness of samples, which helps support the visible improvement in fatigue performance. Additional data is needed however to truly understand the effects of each treatment in order to complete the S-N curves and develop the guidelines for incorporation in the DASH process.

FUTURE WORK

This fundamental study is the first step in creating a series of design rules and variables for the DASH process. With fully defined S-N curves, identification of crack initiation sites, and determination of failure mechanisms for AM metals, the following would be attainable in DASH: (1) more robust calculations for sacrificial support size, (2) optimized amounts for machining allowances on critical features, (3) more accurate fixturing in the CNC machine, (4) minimization of required toolpaths to achieve tolerance specifications, and more. Ultimately, this would mean that metal AM could be used for production of functional components in industries that need toleranced solutions for small batch production operations.

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REFERENCES

- [1] Srinivasan, Harshad. "From Art to Finished Part: The D.A.S.H Hybrid Manufacturing Process." 2016 Additive Manufacturing and Logistics Symposium. Raleigh, NC. 2016.
- [2] Frank, Matthew C., et al. "Direct Additive Subtractive Hybrid Manufacturing (DASH) - An Out of Envelope Method." Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, Austin TX, Aug. 2017.
<https://sffsymposium.engr.utexas.edu/sites/default/files/2017/Manuscripts/DirectAdditiveSubtractiveHybridManufacturing.pdf>

- [3] ISO/ASTM 52921-13(E): Standard Terminology for Additive Manufacturing - Coordinate Systems and Test Methodologies. 2013, <https://compass.astm.org/download/ISOASTM52921.35709.pdf>.
- [4] Ackelid, Ulf. Application of Mechanical Surface Finishing Processes for Roughness Reduction and Fatigue Improvement of Additively Manufactured Ti-6Al-4V Parts. http://www.eam.fau.de/fileadmin/uploads/Events/2016/EBAM_2016/Presentations/Ackelid.pdf.
- [5] Wang, X., et al. "Gradient Structured Copper by Rotationally Accelerated Shot Peening." *Journal of Materials Science & Technology*, vol. 33, no. 7, July 2017, pp. 758–61. ScienceDirect, doi:10.1016/j.jmst.2016.11.006.

RECENT DEVELOPMENTS IN FIBER-REINFORCED ADDITIVE MANUFACTURING OF INJECTION MOLDING INSERTS

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INTRODUCTION

Digitization and industry 4.0 (I4.0) processes have increased the need and possibilities of smart, flexible, and cost efficient production. Focusing this development to the injection molding (IM) industry, IM inserts manufactured from additive manufacturing (AM) vat photopolymerization (VP) have been developed and increased their market share over the past years. [1]–[3] The inserts comprise the possibility of digital part development at low entry costs and therefore are a technology used for pilot production.

The authors conclude that challenges regarding the lifetime of polymer inserts in connection with the involvement of thermal stresses, crack propagation, and molding cycle time can be tackled by fiber-reinforced AM. Lifetime has been increased by a factor of 20 reaching an average lifetime of 4.500 shots and an increase the attractiveness of the inserts for prototyping and pilot production has been achieved. So far, short, virgin, and unseized carbon fibers (CFs) with diameters of 7.2 μm and average lengths of 100 μm as well as glass fibers (GFs) have been utilized in a number of investigations.

Considering the increased lifetime of the discussed inserts, further factors such as the molding cycle time increase in their significance for further developments. The tested molding configurations included a 1.5 s mold closing and injection, 7 s packing and cooling, 1.5 s mold opening and ejection, followed by 10 s natural cooling. Both packing and cooling, as well as natural cooling are characterized by longer times as required for competitive materials such as brass, aluminum,

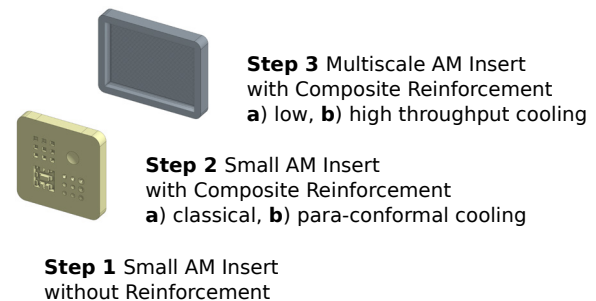


FIGURE 1. AM IM insert development steps considering fiber-reinforcement and cooling as crucial factor for an enlargement of the application space.

steel, and silicon carbide (SiC) and are tackled by the presented research.

SYNTHESIS OF CURRENT CAPABILITIES

The authors have performed both experimental and numerical investigations to face the challenges described below facing moreover the challenge of effusivity of polymer insert material in an IM process.

Heat Transfer and Cooling Mechanisms

Numerical simulations as well as investigations using a thermographic camera were conducted in order to understand the modified cooling mechanisms of polymer inserts produced by VP. An understanding of both convectional as well as liquid cooling was achieved for multiple insert development steps shown in Figure 1. [4], [5]

The inserts were modeled with dimensions of (20 x 20 x 2.7) mm³ (small inserts) and (60 x 80 x 10) mm³ (multiscale inserts) including effusivity in relation to the thermal properties in comparison to the injected acrylonitrile butadiene styrene (ABS) material. The interface temperature was calcu-

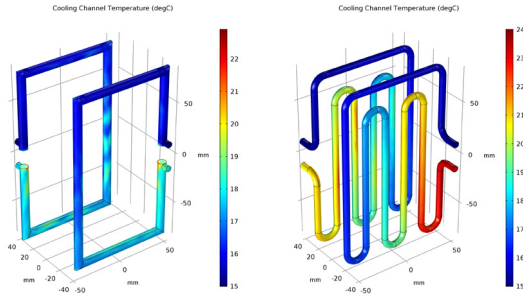


FIGURE 2. Temperature of conventional (left) and para-conformal (right) cooling channels at a throughput of 5 L/min. Due to the improved flowability of the fluid in the channels with rounded corners, a higher throughput of up to 10 L/min is possible.

lated as

$$T_i = \frac{b_1 T_1 + b_2 T_2}{b_1 + b_2}, \quad (1)$$

$$b_i = \sqrt{k_i \rho_i c_{p_i}}. \quad (2)$$

Whereas:

- T_i = temperature at interface
- k_i = thermal conductivity
- ρ_i = density
- c_{p_i} = heat capacity

This resulted in an interface temperature with ABS of 32.2 °C (steel), 121.0 °C (photopolymer), 30.0 °C (brass), and 27.4 °C (SiC) whereas a 4-fold difference between the photopolymer and the comparison materials can be noted and significantly influences the insert temperature. [4]

Investigations confirmed the crucial importance of advanced cooling mechanisms such as para-conformal cooling where the standardized mold geometry is modified by techniques available for conformal cooling providing a uniform surface temperature and therefore reducing thermal stresses. The amount of heat removed from the system by the cooling liquid has been increased from 2.9 kW to 5.7 kW after the change from conventional cooling to para-conformal cooling shown in Figure 2. This factor reaches significance as insert and part volumes increase while at the same time utilizing the freedom of design that comes with AM techniques.

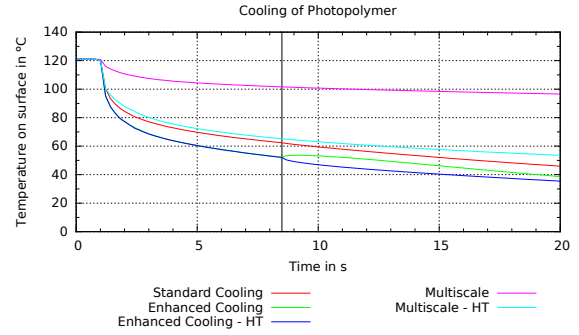


FIGURE 3. Surface temperature of small AM inserts with standard cooling, enhanced cooling, with and without high throughput (HT, 10 L/min), and multiscale inserts.

By the use of enhanced cooling, the overall temperature of the insert was reduced (as shown in Figure 3), which allows a reduction of the natural cooling time by 6 s while starting the molding cycle at the same insert temperature. The use of larger insert geometries corresponds to longer cooling times, which can be reduced by an advanced cooling of the standardized steel mold in the background.

Fiber Orientation and Control

Conventional VP processes include a flat build plate in a bottom-up or top-down machine whereas the part is manufactured in layers at usual heights of lower 2-digit μm forcing the fibers into a layered orientation by removing one degree of freedom (DOF).

Simulations have been conducted predicting the final fiber orientation as a result of the fluid flow of the resin due to moving boundaries representing the build plate. Several potential solutions have been found to control the fiber orientation and increase the orientation angles out of the build plate orientation. [6]

Streamline analysis was performed according to [7]–[9] predicting the fiber orientation in bottom-up and top-down technologies including a modified build plate design. The usually horizontal alignment of fibers in bottom-up printing processes can be changed in top-down processes and isotropic fiber orientation can be achieved by a modified build plate with cylindrical, vertical holes shown in Figure 4.

Practical experiments at an open top-down machine have shown furthermore an improvement in warping of the free surface due to surface tension

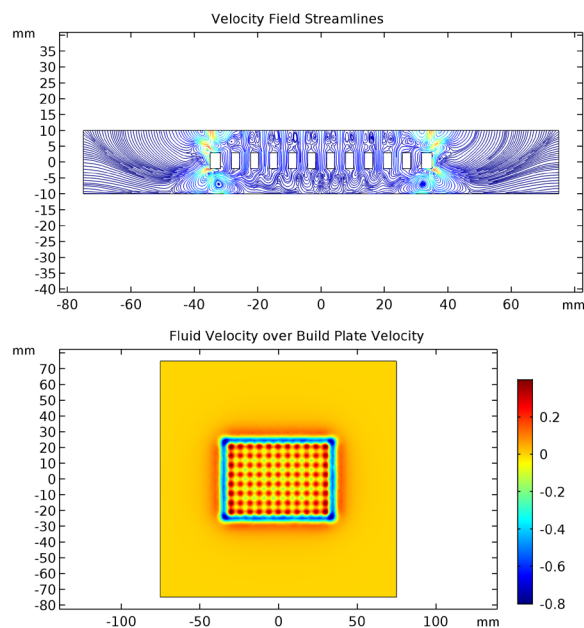


FIGURE 4. Streamlines as fiber orientation prediction (top) and vertical velocity factors normalized by the build plate velocity (bottom) for a modified geometry with vertical cylindrical holes in the build plate.

of the thermoset photopolymer resin when using modified build plates. Due to the suction effect of the moving build plate, a velocity is induced in the fluid, which again results in a warped surface. The waiting time for relaxation of the surface tension effect has been reduced by 50 % when using the modified build plate design. The results also allow the conclusion that fiber orientation in a thermoset photopolymer can be controlled by the orientation of the part in the resin vat.

FAILURE MECHANISMS

Cracks represent the biggest threat for insert lifetime and their understanding is crucial for a further enhancement of lifetime and product quality.

Fiber-Matrix Interface and Internal Defects

Investigations on thermal curing mechanisms of multi-component photopolymer resins have been conducted facing the low level of chemical bonding of CFs (and less GFs) to the curing polymer. It could be concluded that a combination of thermal and optical energy introduction during the printing process allows an improved fiber-matrix interface quantified by an increased strength and stiffness of the final part.

Visualized in Figure 5, it was possible to increase the specific load at break by a factor

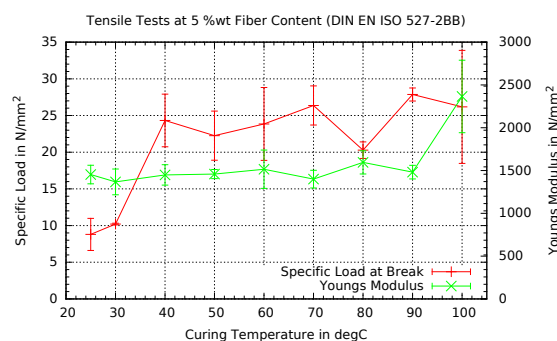


FIGURE 5. Tensile properties of a thermoset photopolymer with 5 %wt glass fiber content at different curing temperatures utilizing both thermal and optical curing of the photopolymer.

of up to 3 at certain cases utilizing both optical as well as thermal curing of the thermoset photopolymer filled with 5 %wt glass fiber. 50 % trimethylolpropane triacrylate containing 600 ppm monomethyl ether hydroquinone as inhibitor in combination with 50 % 2-Hydroxyethyl methacrylate containing 250 ppm monomethyl ether hydroquinone as inhibitor and 0.2 % Irgacure 819 (chemical name: Bis(2,4,6-trimethylbenzoyl)-phenylphosphineoxide) was utilized as thermoset photopolymer. Youngs modulus was improved at higher temperatures whereas a significant difference was measured at 80 °C following investigations presented in [10] concluding a gelation of the thermoset photopolymer at higher temperatures.

Other weakening factors such as air intrusions have been investigated using X-ray computed tomography (CT) whereas a significant potential for improvement has been identified, which can be realized by reducing the air intrusion during both the mixture and the manufacturing process. Potential solutions under investigation are a modified stirring mechanism as well as a vacuum mixture, which is already in use e.g. for cold-molding of probes for scanning electron microscopy (SEM). [11]

Crack Propagation and Fiber Alignment

It could be shown by the use of SEM, CT, and optical microscopy analysis that two types of cracks can be identified: (1) smaller surface cracks propagating over the heated surface in a random orientation perpendicular to the surface; and (2) deep cracks penetrating the insert up to 1.8 mm, oriented in parallel to the printed layers (if existing, and therefore also in parallel to the fiber ori-

entation) and finally leading to a total failure of the part. Examples are given in Figure 6 showing both randomly oriented surface cracks as well as penetrating cracks oriented along the printed layer and therefore the fibers. [11], [12]

X-ray tomography was conducted using a "ZEISS XRadia 410 Versa" device at an operation voltage of 40 kV and a power of 10 W using low energy 1 (LE1) filter and a macro objective (LFOV) or a 4X objective. A resolution of 2 μm was obtained as highest resolution. Prior investigations on the fiber orientation during a layer-wise manufacturing process in a bottom-up machine were confirmed using an elliptic approximation of the resolved fibers following the method presented in [13]. [11] A tensor estimation for one of three sample regions is shown in Figure 7 for fiber orientation outside of the printing plane. Orientation along the printed plane is randomly distributed.

Surface cracks have a limited influence on the surface quality of the final product if the injection pressure is reduced and the representation of the surface is limited. Otherwise, the importance of surface quality needs to be considered in the context of an internal prototyping process. Surface roughness was concluded to be stable at an average of $R_a = 0.45 \mu\text{m}$.

It could be shown that fibers have a significant influence on the crack propagation which is reduced to 1.25 % as compared to a non-reinforced polymer. The concluded crack orientation and dimensions lead to the understanding that an isotropic fiber orientation should be achieved for further development of AM IM inserts since the material deals both with periodical mechanical and thermal stresses during the process.

Life Cycle and Environmental Factors

A full life cycle assessment (LCA) has been conducted investigating the influence of CFs on the environmental impact of IM inserts in comparison to conventional materials such as brass, steel, and aluminum under the consideration of contributions by [14]–[17]. The improved lifetime plays an important role in the reduction of the investigated factors of global warming potential (GWP) and human toxicity (HT). Both AM and computer numerical control (CNC) machining were investigated in a comparison assessment which did not include the injection molding process itself since the process is identical for both process chains. The boundaries are shown in Figure 8 including

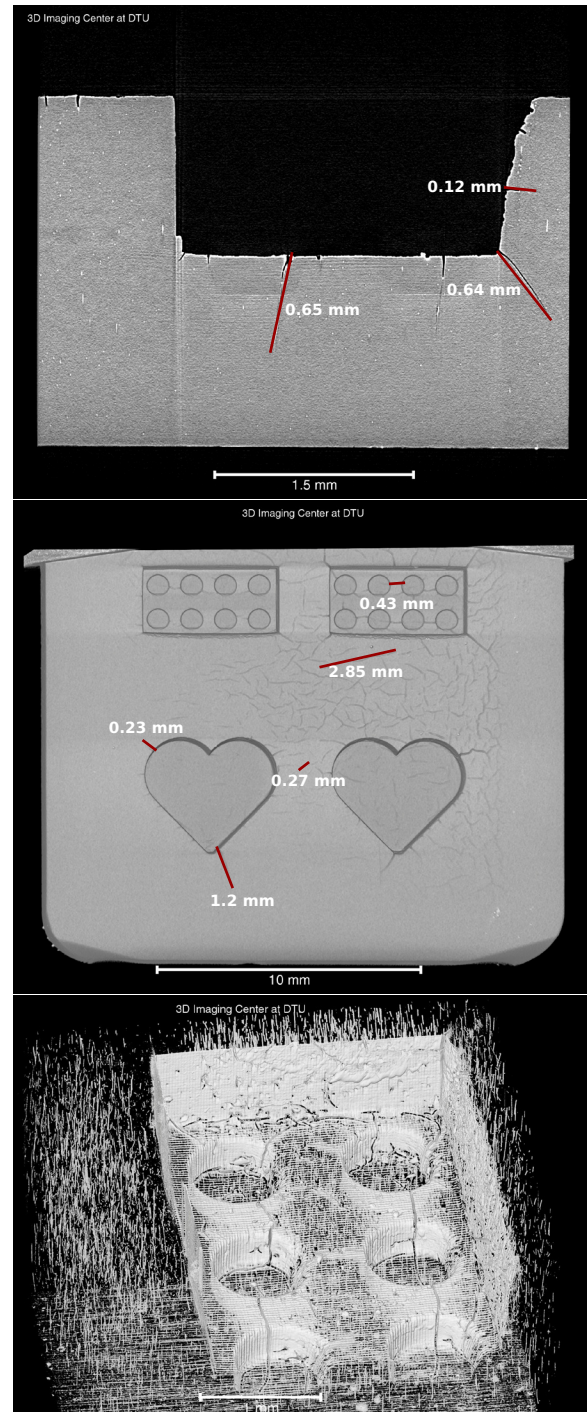


FIGURE 6. Deep cracks aligned along the printed layers and propagated due to the corner effect of thermal and mechanical stresses (top) and randomly oriented surface cracks (middle) with a higher density on the right side of the image due to the orientation of the material injection from the right. Individually identified fibers in an overview (bottom).

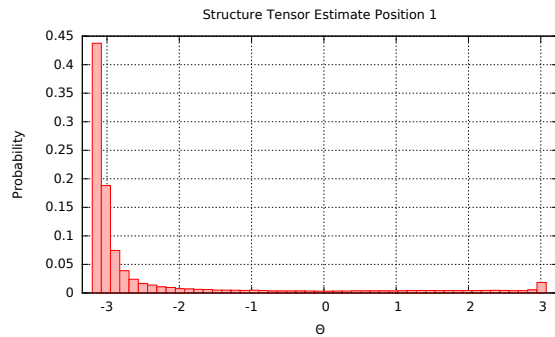


FIGURE 7. Structure tensor estimation outside the printing layers. Due to geometrical restrictions in a bottom-up printing process, only a slight angle between the printed plane and the fiber is possible.

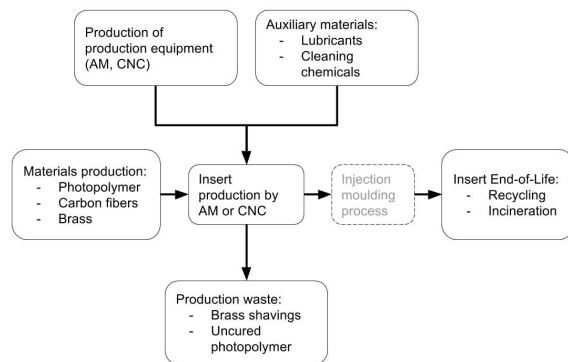


FIGURE 8. System boundaries of the conducted LCA with exemption of the IM process itself.

the influencing factors such as materials used in the production process and waste generation.

The LCA showed a huge potential of production optimization in such a way that the amount of wasted resin is reduced therefore especially reducing the HT level. Moreover, there are currently no sustainable end of life (EoL) scenarios available. [18]

CONCLUSION

While industrial applications slowly start their appearance on the market for non-fiber-reinforced IM inserts, fiber-reinforcement has shown to bring further improvement to the material. With an overall understanding of the crack propagation mechanisms in correlation to the fiber orientation as well as a predictive description of flow mechanisms in the resin vat, a determined fiber orientation can be achieved helping to further improve the mechanical and thermal properties of the inserts. These properties play an important role in

parameters for further industrial production when directly influencing the molding cycle time. Since the natural cooling time has been reduced by over 50 % and LCA showed a significant reaction on the lifetime of the inserts, they can be considered a sustainable method for future production in a smart, digital fabrication environment.

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References

- [1] Á. Oroszlany, P. Nagy, and J. G. Kovács, "Injection molding of degradable interference screws into polymeric mold," in *Materials Science Forum*, Trans Tech Publ, vol. 659, 2010, pp. 73–77.
- [2] T. Hofstätter, D. B. Pedersen, G. Tosello, and H. N. Hansen, "Challenges and opportunities of fibre-reinforced polymers in additive manufacturing with focus on industrial applications," in *euspen and ASPE Special Interest Group Meeting: Additive Manufacturing*, The European Society for Precision Engineering and Nanotechnology, 2017.
- [3] T. Mitterlehner, C. Beisteiner, H. Rieger, P. Dunzendorfer, and G. Steinbichler, "Back injection molding with additiv manufactured mold inserts using all-inkjet printed substrates," in *Technical conference of the Society of Plastics Engineers*, 2017.
- [4] T. Hofstätter, D. B. Pedersen, G. Tosello, and H. N. Hansen, "Thermal behaviour of additively manufactured injection moulding inserts," in *euspen's 18th International Conference & Exhibition*, The European Society for Precision Engineering and Nanotechnology, 2018.
- [5] —, "Evolution of additively manufactured injection molding inserts investigated by thermal simulations," in *34th Annual Meeting of the Polymer Processing Society (PPS34)*, 2018.

- [6] T. Hofstätter, J. Spangenberg, D. B. Pedersen, G. Tosello, and H. N. Hansen, "Flow characteristics of a thermoset fiber composite photopolymer resin in a vat polymerization additive manufacturing process," in *34th Annual Meeting of the Polymer Processing Society (PPS34)*, 2018.
- [7] F. Folgar and C. L. Tucker III, "Orientation behavior of fibers in concentrated suspensions," *Journal of reinforced plastics and composites*, vol. 3, no. 2, pp. 98–119, 1984.
- [8] R. C. Givler, M. J. Crochet, and R. B. Pipes, "Numerical prediction of fiber orientation in dilute suspensions," *Journal of composite materials*, vol. 17, no. 4, pp. 330–343, 1983.
- [9] K. Chiba and K. Nakamura, "Numerical solution of fiber suspension flow through a complex channel," *Journal of non-newtonian fluid mechanics*, vol. 78, no. 2-3, pp. 167–185, 1998.
- [10] J. K. Gillham, "Formation and properties of thermosetting and high tg polymeric materials," *Polymer Engineering & Science*, vol. 26, no. 20, pp. 1429–1433, 1986.
- [11] T. Hofstätter, S. Baier, C. Gundlach, D. B. Pedersen, G. Tosello, and H. N. Hansen, "Internal fiber structure of a high-performing, additively manufactured injection molding insert," in *34th Annual Meeting of the Polymer Processing Society (PPS34)*, 2018.
- [12] T. Hofstätter, M. Mischkot, D. B. Pedersen, G. Tosello, and H. N. Hansen, "Evolution of surface texture and cracks during injection molding of fiber-reinforced, additively-manufactured, injection molding inserts," in *Proceedings of ASPE Summer Topical Meeting 2016*, ASPE—The American Society for Precision Engineering, 2016.
- [13] M. Krause, J. M. Hausherr, B. Burgeth, C. Herrmann, and W. Krenkel, "Determination of fibre orientation in composites using the structure tensor and local x-ray transform," *Journal of Materials Science*, vol. 45, no. 4, pp. 888–896, 2010.
- [14] J. Faludi, C. Bayley, S. Bhogal, and M. Iribarne, "Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment," *Rapid Prototyping Journal*, vol. 21, no. 1, pp. 14–33, 2015.
- [15] J. Bours, B. Adzima, S. Gladwin, J. Cabral, and S. Mau, "Addressing hazardous implications of additive manufacturing: Complementing life cycle assessment with a framework for evaluating direct human health and environmental impacts," *Journal of Industrial Ecology*, vol. 21, no. S1, 2017.
- [16] K. Kellens, M. Baumers, T. G. Gutowski, W. Flanagan, R. Lifset, and J. R. Duflou, "Environmental dimensions of additive manufacturing: Mapping application domains and their environmental implications," *Journal of Industrial Ecology*, vol. 21, no. S1, 2017.
- [17] A. Jayal, F. Badurdeen, O. Dillon Jr, and I. Jawahir, "Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels," *CIRP Journal of Manufacturing Science and Technology*, vol. 2, no. 3, pp. 144–152, 2010.
- [18] T. Hofstätter, P. M. Stotz, N. Bey, D. B. Pedersen, G. Tosello, and H. N. Hansen, "Life cycle assessment of fiber-reinforced additive manufacturing for injection molding insert production," in *Sustain 2017*, Technical University of Denmark (DTU), 2017.

CORRELATING VOLUME AND SURFACE FEATURES IN ADDITIVELY MANUFACTURED METAL PARTS

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INTRODUCTION

Additive manufacture (AM) is starting to become viable as an option for the production of high value parts that were not previously feasible because of spatial restrictions in machining operations. Metal AM, particularly, presents an attractive method of manufacture for parts in the biomedical and aerospace industries. However, notable barriers exist towards the adoption of AM technologies in industry, the most significant of which relates to requirements for further understanding of AM processes [1].

It is well accepted that measurement and analysis of manufactured surfaces can be used to develop an understanding of processes [2,3]. Surface topography measurement has been used extensively for this purpose in metal AM [4], but the majority of recent work solely involves examination of ISO 25178-2 [5] surface parameters. While these (and other) parameters are often vital in part verification, there exists a tendency to rely upon them for surface analysis and pay less attention to the specific features present on surfaces, which can in many cases contribute towards developing a deep understanding of a process. In recent work by the authors [6–8], we presented investigations of metal AM surface features, and novel methods of characterising these features. In this work, we discussed how such features can be considered a ‘process fingerprint’, telling a story about the physical interactions occurring during the manufacturing process.

Metal AM parts are known to suffer from porosity, resulting from various physical phenomena occurring during processing [9]. In previous work by the authors [10], an analysis was performed of the influence of melt strategy on porosity in electron beam powder bed fusion (EBPBF) parts, by using X-ray computed tomography (XCT). In

this work, correlation was found between porosity and process conditions, potentially facilitating the reduction, or even elimination, of such porosity in future part production.

Porosity analysis using XCT is of great value in an academic setting and provides significant insight for researchers working on process development. For the industrialist, however, measurement of parts by XCT is expensive and slow [11]. If it is possible to correlate internal features (such as porosity) to external features (such as those present on a surface), it may be possible to infer information about a part volume from the process fingerprint remaining on the part surface. To this end, we present initial attempts to correlate internal porosity to surface features.

METHODOLOGY

In this work, we perform coherence scanning interferometry [12] measurements of surface features, present on a variety of (10.6 × 10.6 × 25.0) mm Ti6Al4V samples produced by EBPBF with varying process parameters (summarised in Table 1, and described in more detail elsewhere [10]). Specifically, we examine the geometry of individual weld tracks on the surfaces of samples [7,8], examining variation in weld track width along track length using a preliminary customised measurement pipeline. A description of this preliminary pipeline is presented in figure 1.

The methodology used progressed as follows. Measurements of the final weld track produced during manufacture of individual samples (the only weld track not partially covered by neighbouring weld tracks) were made using a Zygo Newview 8300 coherence scanning interferometer (CSI) [13] equipped with a 20× magnification objective (numerical aperture 0.4). The measurement was performed with optimised

source and detection settings (as discussed in [12]). The measured region (approximately $9.5 \text{ mm} \times 1.5 \text{ mm}$) was obtained by stitching of individual height images, and was equivalent to an area slightly larger than the weld tracks of interest. The pixel size used was $0.41 \mu\text{m}$ and the Sparrow optical resolution was $0.68 \mu\text{m}$. Stitching was performed in Zygo's proprietary software.

TABLE 1: Samples examined in this study. Full details available in ref. [10].

Sample designation	Modification
C0	None (control: speed function 36 & line offset 0.2 mm)
C7	Turning function disabled
S1	Speed function 28
S2	Speed function 20
S3	Speed function 12
L2	Line offset 0.1 mm

The raw data were processed using MountainsMap by DigitalSurf [14]. A levelling operation was initially performed on datasets in the form of a least-squares mean plane subtraction. Data were then filtered using a Gaussian convolution filter with a 0.8 mm cut-off, equivalent to the approximate width of a weld track. Following this operation, an ISO 25178-2 [5] morphologic segmentation was performed on the data, using 1 % of the S_z value (Wolf pruning) and 0.1 % of the total area (area pruning). Segments surrounding the weld tracks were manually removed from the data in order to

separate the weld track of interest from the surrounding surface. The remaining segments were then used as masks and applied to the levelled raw data, resulting in height maps of individual weld tracks. Weld track widths were then manually measured along the length of the tracks, at approximately forty regularly spaced intervals. Width data for six samples were acquired and plotted against the position along the axis of the weld track.

Average weld track widths were then calculated and plotted against porosity for the examined samples (previously reported in [10]), acquired using a custom Nikon 225/320 kV XCT system.

RESULTS AND DISCUSSION

Quantification of the weld track widths with position revealed decreasing width along the examined weld track (see figure 2). This effect was true for all of the samples examined along a length of approximately 9 mm , indicating that melt pool conditions were not constant during the fabrication of the last weld track. This finding may imply that conditions were not constant also during the fabrication of the entire sample (to be verified in future investigations). Such non-uniformity could be inferred from previously published results regarding a non-homogenous distribution of porosity within similar samples [10], but this result confirms the hypothesis by direct measurement of the weld track width. Further investigation of this phenomenon may allow for on-the-fly tuning of process parameters to increase process stability and reduce the creation

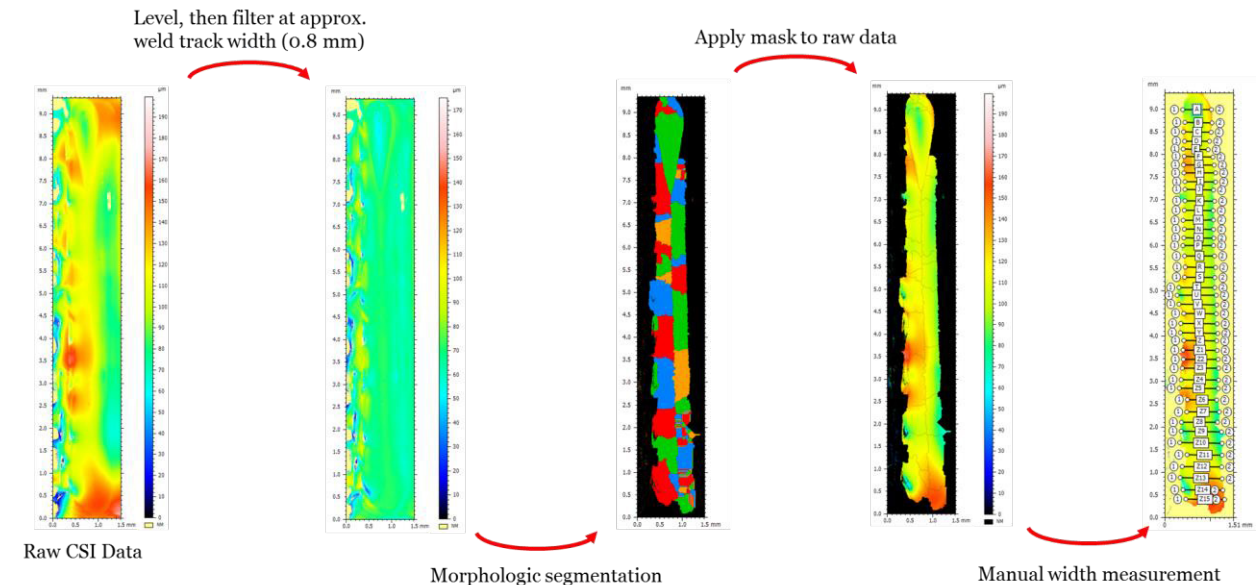


FIGURE 1. Weld track width measurement procedure.

of defects during the build. The caveat to this finding is that, while it is likely to be the case, there is currently no proof that weld track width correlates to melt pool depth (shown previously to have an effect on porosity formation [15]) and so further investigation is required to verify that this is the case. However, assuming a consistent beam spot size (as was the case in these conditions) it is not unreasonable to assume a positive relationship between weld track width and depth, and thus we can make inferences about the relative melt depths of different conditions, even if the absolute values remain hidden.

In previous work [10], analysis of the porosity present in these samples showed a repeatable, non-uniform, distribution of defects along weld tracks, which Tammis-Williams et al. suggested was a result of weld tracks increasing in width along their length. At the time, information about the local weld track size was not available. When

weld track measurement results are considered, the converse appears to be true, with weld tracks decreasing in width along their lengths (figure 2); a new interpretation of the pore distribution is therefore required. From the data, it is likely that pores appear most commonly at the end of weld tracks, as opposed to at the beginning (as previously suggested in [10]), though further investigation is required to successfully explain why this is the case. It should be remembered that the vast majority of pores detected in these samples had an appearance suggesting they were caused by gas bubbles trapped in the melt [10]. It is apparent that the change in melt pool size is accompanied by a change in the probability of cavities forming in the build, including those caused by gas bubbles remaining trapped in the melt following solidification. With further investigation it may be possible to predict local porosity populations within parts.

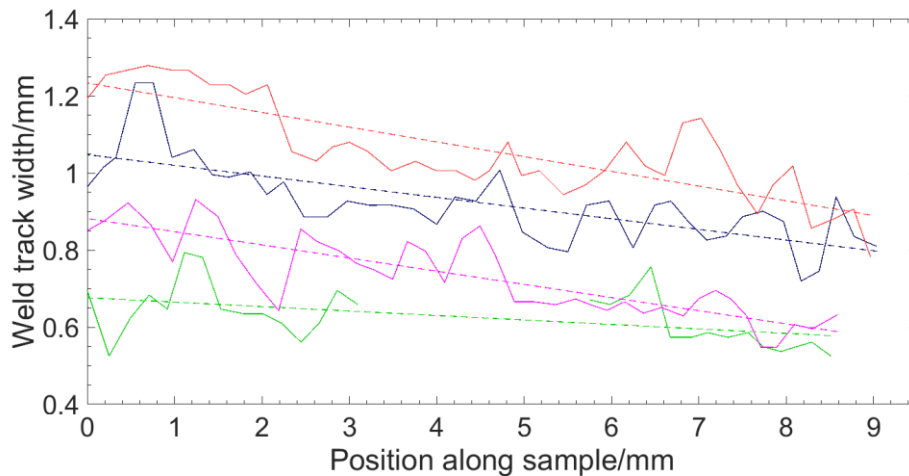


FIGURE 2. Weld track width along track length for 4 samples of varying speed (C0, S1-S3 in ref. [10])

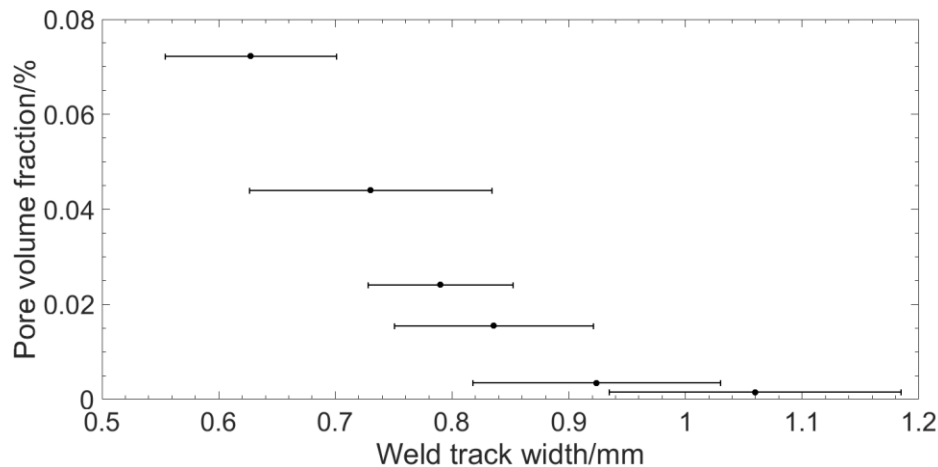


FIGURE 3. Correlation between pore volume and track width. Error bars are standard deviations.

While a quantitative correlation between local weld track width and pore population is yet to be defined, the overall global relationship is already apparent from the limited results presented here (figure 3). It is noteworthy and encouraging for future directions of this work that all the measured data appeared to fit on the same trend line, despite samples being made with a number of modifications. In addition to a range of overall energy densities and line energies being used, changes were made to the hatch offset, and samples were manufactured using both constant and variable beam speeds. Moreover, when the pore population is plotted against line energy, while a trend can be observed, the scatter is significantly increased (figure 4). Thus, using line energy alone is unsuitable for predicting the pore population, whereas the weld track width method (as used here), with further investigation, may prove to be more robust. This finding implies that it may be possible to use surface measurement to infer local and global porosity populations within components. This is a potentially interesting finding as, if confidence can be established in the technique, the technique may alleviate the requirement for XCT scanning in some industrial cases. XCT is well known to be costly in terms of monetary value and in time [11], and so the technique reported here potentially represents a significant saving in a number of industrial settings.

A note should be made about the validity of the width measurement technique. Specifically, it is the case that this initial research is based upon manual measurements of weld track width on the surfaces of electron beam melted samples, and is currently hindered by the requirement for

human operation in weld track width measurements. In an ideal scenario, the method of weld track width measurement would be entirely algorithmic and have no reliance on human operator choices (such as that presented in [7]). Development of such an algorithmic method is planned for the future.

CONCLUSIONS AND FUTURE WORK

There is a link between weld track width and part porosity, with wider weld tracks resulting in lower porosity. Variation in width along weld tracks also has previously been shown to have an influence on the position of pores within parts [10]. The reasons behind observed track width variations in parts are to be explored, but application of acquired knowledge about width variations may allow for pore reduction in future part production, by deliberately varying parameters in-process to influence track width.

A number of avenues of future research have been identified during this work. In future research, we aim to elaborate upon these initial findings by developing a stable measurement pipeline to algorithmically determine weld track geometry in a repeatable manner (similar to that presented in [8]), and to apply this pipeline to a series of samples, both electron beam melted and laser melted. These samples will be representative of varying degrees of 'reality', i.e. as built samples, weld tracks deposited on existing metal AM surfaces and single weld tracks deposited on base plates. With these new techniques, we hope also to answer the questions raised by this research, examining why pores appear at the end of weld tracks. Correlation of the experimental findings with

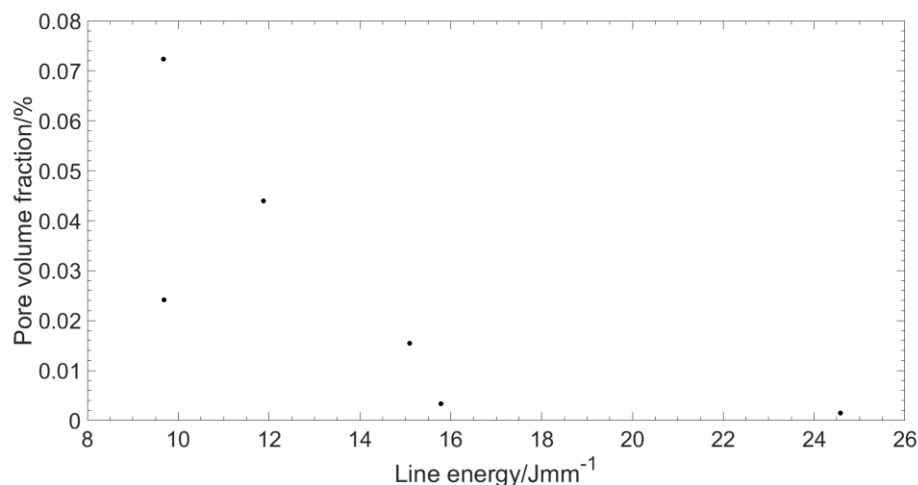


FIGURE 4. Correlation between pore volume and line energy.

theoretical models will also be sought.

Measurement of weld tracks in a repeatable manner will allow for the acquisition of a deep understanding of weld track geometry, and through correlation to porosity data acquired using XCT measurement, could allow for the detection and prevention of subsurface defects during processing.

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REFERENCES

- [1] Dickens P, Wimpenny D, Wilson R. Additive Manufacturing UK 2025. UK AM Strategy Steering Group. Nottingham: 2016.
- [2] Thomas T R. Roughness and function. *Surf Topogr Metrol Prop*. 2014; 2: 014001.
- [3] Benardos P G, Vosniakos G C. Predicting surface roughness in machining: A review. *Int J Mach Tools Manuf*. 2003; 43: 833-844.
- [4] Townsend A, Senin N, Blunt L, Leach R K, Taylor J S. Surface texture metrology for metal additive manufacturing: a review. *Precis Eng*. 2016; 46: 34-47.
- [5] ISO 25178-2 Geometrical product specifications (GPS) -- surface texture: areal -- part 2: terms, definitions and surface texture parameters. International organisation for standardisation. Geneva: 2012.
- [6] Thompson A, Senin N, Giusca C, Leach R K. Topography of selectively laser melted surfaces: A comparison of different measurement methods. *Ann CIRP*. 2017; 66: 543-546.
- [7] Senin N, Thompson A, Leach R K. Characterisation of the topography of metal additive surface features with different measurement technologies. *Meas Sci Technol*. 2017; 28: 95003.
- [8] Senin N, Thompson A, Leach R K. Feature-based characterisation of signature topography in laser powder bed fusion of metals. *Meas Sci Technol*. 2017; 29: 45009.
- [9] Maskery I, Aboulkhair N T, Corfield M R, Tuck C, Clare A T, Leach R K, Wildman R D, Ashcroft I A, Hague R J M. Quantification and characterisation of porosity in selectively laser melted Al-Si10-Mg using x-ray computed tomography. *Mater Charact*. 2015; 111: 193-204.
- [10] Tammas-Williams S, Zhao H, Léonard F, Derguti F, Todd I, Prangnell P B. XCT analysis of the influence of melt strategies on defect population in Ti-6Al-4V components manufactured by selective electron beam melting. *Mater Charact*. 2015; 102: 47-61.
- [11] Thompson A, Maskery I, Leach R K. X-ray computed tomography for additive manufacturing: a review. *Meas Sci Technol*. 2016; 27: 72001.
- [12] Gomez C, Su R, Thompson A, DiSciacca J, Lawes S, Leach R K. Optimisation of surface measurement for metal additive manufacturing using coherence scanning interferometry. *Opt Eng*. 2017; 56: 111714.
- [13] de Groot P. Coherence scanning interferometry. In: *Optical measurement of surface topography*. Ed: Leach R K. Berlin: 2011; 187-208.
- [14] Digital Surf 2018 Mountains® surface imaging & metrology software (Available at: <http://www.digitalsurf.com/en/mntkey.html>. Accessed: 20 June 2018).
- [15] Everton S K, Hirsch M, Stavroulakis P, Leach R K, Clare A T. Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing. *Mater Des*. 2016; 95: 431-45.

DETECTION OF SUBSURFACE DEFECT FOR METAL ADDITIVE MANUFACTURING USING FLASH THERMOGRAPHY

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INTRODUCTIONS

Metal additive manufacturing (AM) faces several quality problems including dimensional accuracy, poor surface finish, and inconsistent material properties. Incorrect process parameters, such as laser power, scan speed and hatch distance, lead to insufficient laser sintering/melting that results in porous and varied internal structure. Gas pores, cracks and unfused powder affect mechanical properties of the final part. X-ray computed tomography (CT) can measure these internal defects, but it is time-consuming, costly, and can only be used ex-situ.

Flash thermography is an alternative non-destructive method to assess subsurface defects. It is quicker and less expensive than X-ray CT. Unlike X-ray CT, a flash thermography system only scans through a short distance below the surface. The scan depth is limited by the size of the defect, that is the scan depth is typically smaller than the width of the defect. It could work for additively manufactured components because the measurement might be made during the fabrication process where the subsurface defects are measured every a few layers.

A flash thermography measurement process includes heating the surface with a high-energy flash pulse and recording the surface temperature cooling after the flash. The surface temperature rise is typically a few degrees. A defect under the surface with a smaller thermal effusivity leads to the surface area above the defect cools slower than a defect-free area because the defect absorbs the heat slower. Therefore, a subsurface defect can be observed in the transient thermal images as an over-heated spot. An improved technique analyzes the transient thermal images by fitting the surface cooling curve in the logarithm scale to a

polynomial function and calculate the second derivative of the fitted curve at each pixel [1]. The peaks of the second derivative corresponds to the thermal diffusion time from the surface to the defect and the depth of the defects. This technique falls short for detecting near-surface defect which has a diffusion time shorter than the flash duration because the cooling curves are essentially analyzed after the flash, thus the second-derivative peak will not present in the measurement. Ideally, the flash duration should be significantly shorter than the thermal diffusion time. A flash quenching technique can shorten the flash duration to a few milliseconds [2], [3], but this flash duration is still too long for the defects seen in additively manufactured metal components. The subsurface pores produced by the power bed fusion processes are reported to be from 50 μm to 500 μm deep [4]. This means the diffusion time for these defects will be shorter than or close to the flash duration. For example, a 200- μm gas pore 200 μm below a stainless steel 316L surface has a diffusion time of approximately 3.5 ms. Therefore, the second-derivative-peak approach cannot be directly adopted.

We investigate the impact of a long flash duration on the measurement of near-surface defects and propose an alternative approach which analyzes the surface cooling curve by fitting a section of the logarithm-scale temperature curve to a linear function. The fitting coefficients show subsurface defects. This technique is tested by a defect artifact created by cutting a series of flat-bottomed slots in a stainless steel 316L plate and an additively fabricated defect artifact.

THEORY

A simple model for analyzing the heat diffusion after a instantaneous thermal flux is to consider

heat diffuse along one direction into a semi-infinite material. The surface temperature decreases by the root square of the time, namely

$$\Delta T = \frac{q_0}{\sqrt{k\rho c\pi t}} \quad (1)$$

where $\Delta T = T - T_0$, that is the surface temperature at any time subtracted by the initial surface temperature before the flash, q_0 is the absorbed input energy, k is the thermal conductivity, ρ is the material density and c is the specific heat capacity. This power function can also be written in a logarithm form, that is

$$\ln(\Delta T) = -0.5 \ln(t) + \ln\left(\frac{q_0}{\sqrt{k\rho c\pi}}\right). \quad (2)$$

It is not necessary to use the natural logarithm scale; other logarithms are also correct. The linear form breaks down when heat propagates to the back wall or to a defect, and the diffusion time is approximately

$$t^* \approx \frac{L}{\pi\alpha}. \quad (3)$$

In a diffusivity measurement, this diffusion time approximately corresponds to the first peak on the second derivative curve [1]. The time of this peak can also be used to estimate the depth of the defect.

SIMULATION

The impact of a long flash duration on the surface cooling curve for a near-surface defect can be studied through a finite element analysis simulation. We conduct such a simulation in the COMSOL Multi-physics software. Figure 1 illustrates the defect artifact under test, that is a stainless steel 316L plate with a 100- μm -radius flat-bottomed hole in the middle. The plate is 2 mm x 2 mm x 0.2 mm and the flat-bottomed hole is 50 μm below the surface. A mesh refinement study is carried out and a physics-controlled mesh routine with a maximum mesh size of 70 μm and a minimum mesh size of 3 μm is determined sufficient to produce accurate results. The flash is modeled as heat flux with a constant power density described by a piece-wise function in the COMSOL. The flash duration are 2 ms and 0.2 ms, respectively. The total energy for the two flash pulses are the same, namely 0.008 J. The flash starts at 1 ms and the simulation runs for 20 ms with a time step of 0.01 ms.

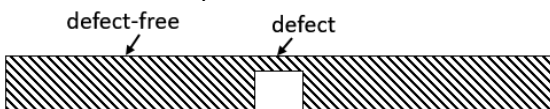


FIGURE 1. A flat-bottom hole defect artifact.

With the 2-ms flash pulse, the surface peak temperature at the defect is approximately 2°C higher than that of a defect-free region (Figure 2 (a)). This is because the flash duration (2 ms) is significantly longer than the diffusion time (0.217 ms) for the 50- μm -deep defect. If the flash duration is equal to or shorter than the diffusion time, the peak temperature of the two curves would be the same (Figure 2(b)).

A long flash duration also changes the surface cooling behavior. The 1D diffusion model (Equation 1) is no longer valid. Instead, the cooling behavior can be approximated by a combination of complex error functions [5]. Therefore, the simple linear relationship between the surface cooling curve ($\log_{10}(\Delta T)$ vs. $\log_{10}(t)$) become nonlinear when the 2 ms flash is used (Figure 2 (c)). The linear cooling curve (Equation 2) requires the flash duration shorter than the diffusion time as shown in Figure 2 (d). The linear region for the defect curve ends approximately 10 frames (0.1 ms) after the flash and linear region for the defect-free curve ends approximately at 2.7 ($10^{2.7} \approx 5$ ms). These values differ from the theoretical diffusion time calculated from Equation 3, namely 0.2 ms and 3.5 ms, respectively, because the flash pulse cannot be assumed as a instantaneous pulse.

Even with the flash duration being much longer than the 0.2-ms diffusion time, the defect curve significantly differs from the defect-free curve, indicating the possibility of detecting the subsurface defects by characterizing the cooling curve at each pixel. We explore fitting 500 frames (5 ms) of the surface temperature data in the logarithm-scale to a linear function, $y=b+cx$, and calculate the fitted coefficients at each pixel. The subsequent coefficient maps are shown in Figure 3. The subsurface defect is shown as the opposite color compared to a defect-free region in the coefficient maps, that is a brighter color in the coefficient b map, and a darker color in the coefficient c map. The boundary of the flat-bottomed hole (outlined in red in the two maps) roughly match the boundary of the defects shown in the coefficient b and c maps.

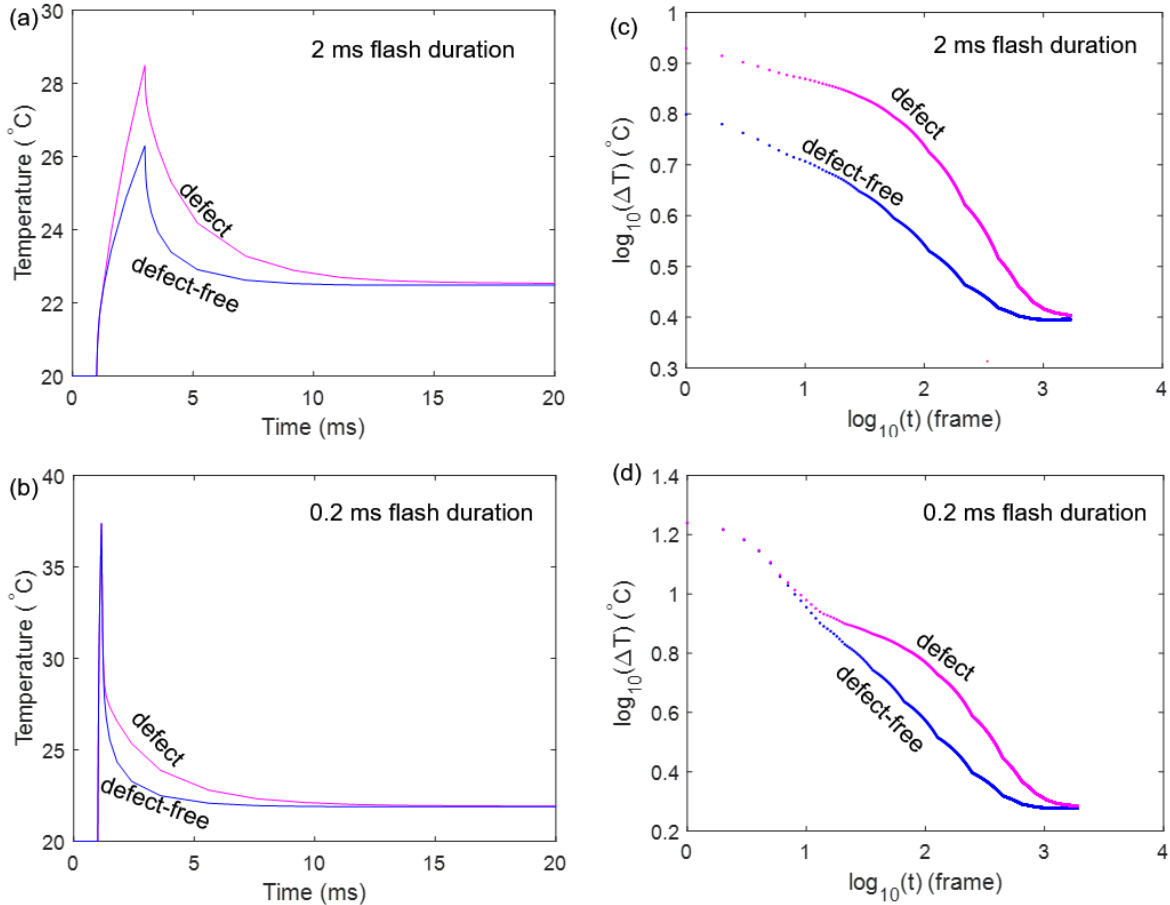


FIGURE 2. The linear-scale and logarithm-scale surface cooling curves on a defect area and a defect-free area with a 2-ms flash and a 0.2-ms flash.

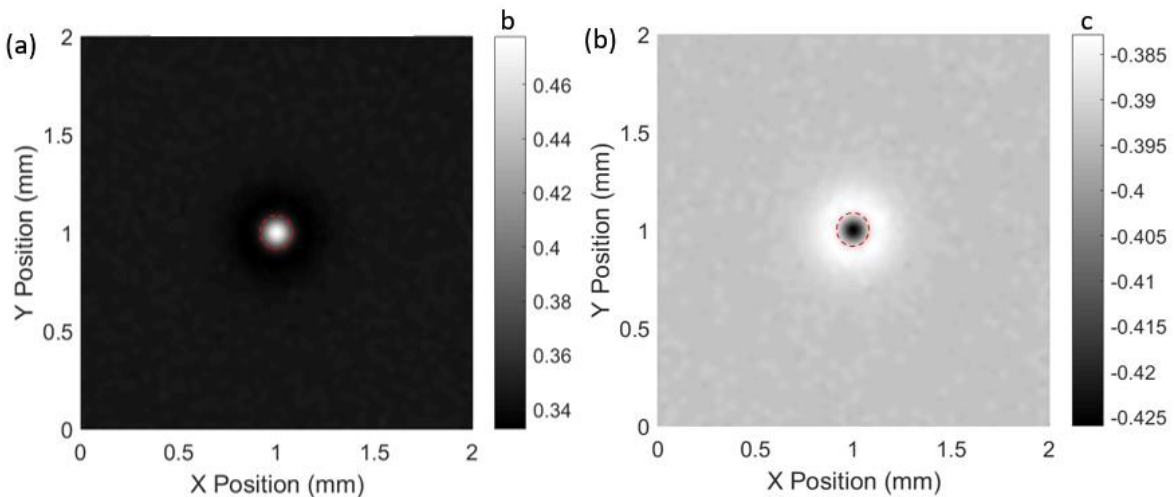


FIGURE 3. The coefficient maps obtained by fitting a section of the logarithm-scale cooling curve to a linear function.

EXPERIMENT

We investigate the applicability of flash thermography to measuring subsurface defects of additively manufactured metal parts using a

slot-cut conventionally fabricated “defect” sample (Figure 4). This sample is made by a 5-mm-thick stainless steel 316L plate with five 0.5-mm-wide slot cuts. The thickness between the top surface

and the slots are 0.3mm, 0.35 mm, 0.4 mm, 0.45 mm and 0.5 mm from the left to the right. The corresponding thermal diffusion time of the five “defects” are approximately 8 ms, 11 ms, 14 ms, 18 ms and 22 ms. Half of the top surface is painted by a thin layer of high-emissivity paint to enhance heat absorption and thermal radiation. This is a common practice for the flash thermography technique because a low emissivity surface decreases the signal-to-noise ratio.

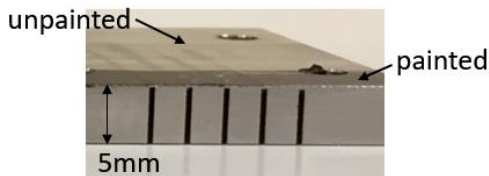


FIGURE 4. A “defect” artifact made by a stainless steel 316L plate with 0.5-mm-wide slot cuts below the surface.

The flash thermography system used in this study consists of a high-energy Xenon flash lamp (Hensel EH pro) and a high-speed thermal camera (FLIR SC5000) with a 54-mm focal length lens as shown in Figure 5. The flash lamp generates a 6kJ pulse with a duration of approximately 10 milliseconds. A polymethyl methacrylate (PMMA) window is placed in front of the lamp to filter wavelengths longer than 3 μm to reduce surface reflections. The camera records the temperature change on the surface with a 328 Hz frame rate for 3 seconds. The camera captures an area of 45 $\times$ 36 mm² on the surface with 320 $\times$ 256 pixels (0.14 $\times$ 0.14 mm² pixel footprint).



FIGURE 5. The experimental setup of the flash thermography system.

We extract a thermal radiation curve at each pixel and subtract the average radiation before the flash from the curve. Then we fit 100 data points

in a section of the cooling curve to a linear function (Figure 6). The fitting coefficients are then calculated using a least-square algorithm. Repeating the linear fitting process for all the pixels gives the two coefficient (b and c) maps as shown in Figure 7.

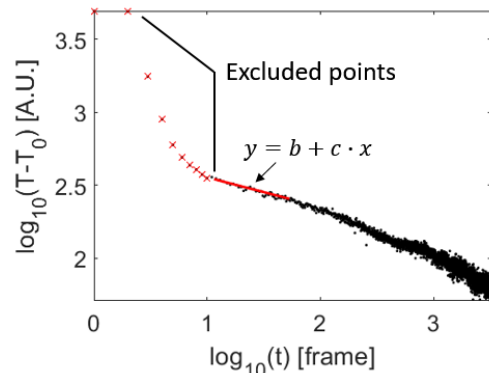


FIGURE 6. Fitting of 100 data points in the log-log scale temperature curve to a linear function.

The measurement shows the defect present as the opposite color compared to the defect-free area, that is a bright pixel in the b map and a dark pixel in the c map. For the painted surface, the contrast between a defect pixel and a defect-free pixel is almost identical for the coefficient b map and the coefficient c map. For the unpainted metal surface, the coefficient b map seems showing more surface texture, while the coefficient c map revealing more subsurface defects. The unpainted metal surface reduces the contrast between the subsurface defect and the defect-free area. The contrast drop is shown by the dynamic range of the color bar, that is a 50% drop for the coefficient b map being and a 70% drop for the coefficient c map. Even though the coefficients have no physical meanings, the contrast between a defect pixel and a defect-free pixel decreases with the defect depth, indicating the possibility of calculating the defect depth with the coefficient value.

A 3D microCT1 of model (Nikon XTH 225 ST) was utilized. The instrument is made up of an x-ray source, a high precision rotatable mount which also moves up and down to give details of the region of interest, a translator which adjusts the magnification and a high-resolution detector system (screen). The sample was placed on the high precision rotatable mount which is located in between the x-ray source and the image detector and the data acquisition features of this facility was set up to reconstruct a voxel size of 36 microns, a voltage of 130KV, and current of 50 μA .

2D scans represented by pixels were then taken at different intervals while the mount was rotating. The images in form of 2D slices extracted from the x-ray CT scans were then reconstructed into 3D volume by means of mathematical algorithms. The algorithm used in this reconstruction was the iterative reconstruction and this was done with the aid of the visualization tool used, VG studio max 2.1. The resulting 3D reconstructed images are represented as voxels. The voxels also represent the attenuation coefficient of x-ray beam energy penetrating the material in 3D space. The VG studio max is then used to further analyze the reconstructed 3D images. The reconstructed images showed surrounding air and artifacts around the samples and this was segmented and a region of interest was created. A detailed defect analysis i.e. measurement of defect diameter, depth and volume estimation was then performed on the different layers of the distinctive types of defects in the sample.

Figure 8 compares the flash thermography coefficient maps, the surface topography measurements and the X-ray CT measurements. The measured sample contains ten additively fabricated “keyhole” defects created by fusing the hole areas with half the normal laser speed. This allows for enough laser power density to cause evaporation of the metal in the melt pool. The evaporation leads to a vapor cavity behind the melt pool, when it collapses, causes the small pores to remain in the metal. The indentation on the surface might be attributed to the loss of material through the vaporization. The first two

“keyholes” on the left are exposed to the air, the third one is covered by one layer of fuse, the fourth one is covered by two layers, and so on. The “keyhole” on the right is covered by eight layers of fuse. The nominal diameter of the open hole is 0.9 mm. The “keyhole” defect can be better understood by combining information of the surface topographies and the X-ray CT measurements. The surface topography lends itself as a faster technique in acquiring information about the locations and estimated diameter of these defects while the X-ray CT validates the surface data and gives more detailed information about the depth profile. Limitations exist in the CT data as the expected defect size can only be distinguished if it is approximately three times larger than the voxel size of the scan. Both surface indentation and subsurface pores are present in the open holes. The surface indentation decreases as more fused layers are covered atop. The indentation nearly disappears after four layers of fuse, while the subsurface pores are presents for all ten defects. According to the simulation and the previous experiment, a subsurface defect appears as a bright spot in the coefficient b map and as a dark spot in the coefficient c map. This trend could not be clearly identified in the measurement of the additively fabricated sample primarily due to the surface texture and indentation greatly hindering the visibility of the subsurface defects. It appears all the features in the flash thermography coefficient maps are associated with either the surface indentation or the surface texture created by laser stripping.

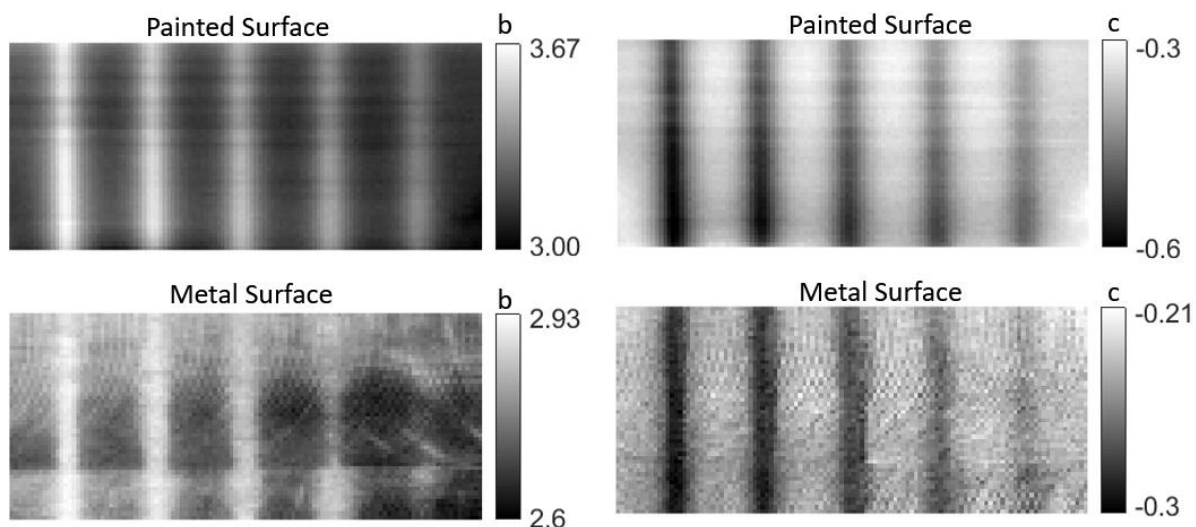


FIGURE 7. The fitting coefficients: (a) and (b) are measured on the painted surface (c) and (d) are measured on the unpainted metal surface.

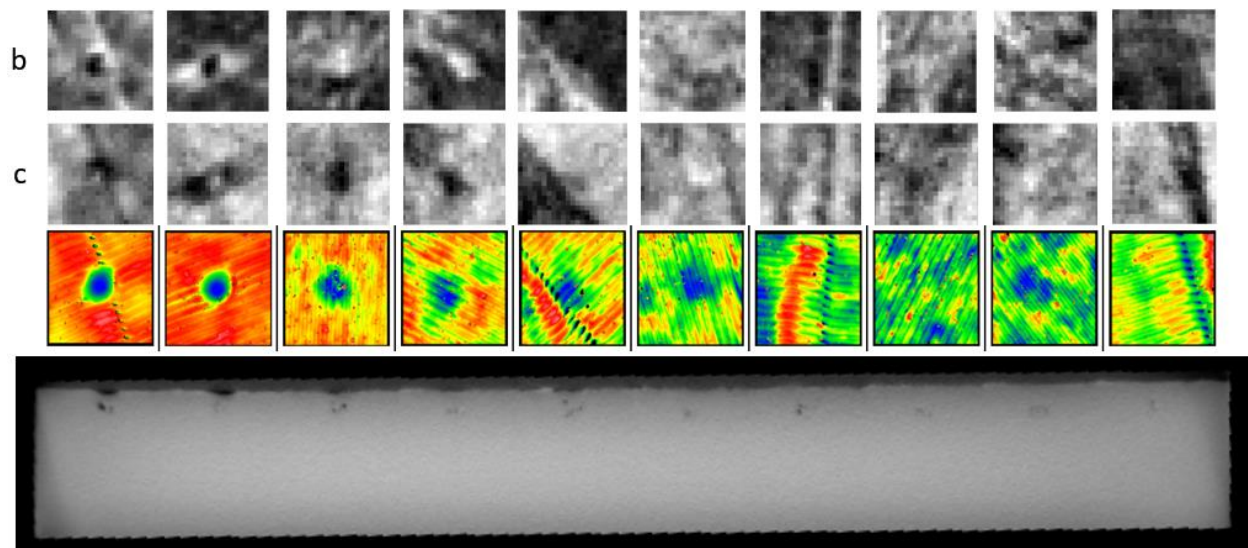


FIGURE 8. The measurements of an additively fabricated defect artifact: the flash thermography coefficient *b* and *c* maps, surface topographies and a cross-section view of an X-ray CT measurement.

CONCLUSION

The metal additive manufacturing process suffers from many quality problems, and one of the biggest problems is related to internal defects such as gas pores, cracks and unfused powder. We investigate a flash thermography technique for in situ inspecting subsurface defects of fused metal layers, and find the diffusion time for the defects seen in additively fabricated components is typically shorter than the flash duration since the subsurface defects are small and the detection limit is close to the surface. This violates the simple 1D diffusion model assumed in many conventional flash thermography techniques. Through a finite element analysis simulation, we find that a long flash duration changes the cooling behavior from an approximate power function to a complex combination of error functions. Therefore, a standard second-derivative-peak analysis method is no longer valid. We investigate an imperial analysis approach by fitting a section of the logarithm-scale cooling curve to a linear function and calculating the fitting coefficients at each pixel. This technique is then tested using a conventionally fabricated “defect” sample with five 0.5-mm wide slots cut under the surface. The subsurface defects are shown as the opposite color of the defect-free region. The coefficient *c* map seems more advantageous for detecting subsurface defects when the measurement is made on the unpainted metal surface. A measurement of an additively fabricated defect artifacts shows the features associated with surface texture and indentation more clearly than

subsurface defects. The subsurface pores are not clearly present mainly because the surface features are too strong and the pores are small and deep.

ACKNOWLEDGMENT

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REFERENCES

- [1] S. M. Shepard, Y. Hou, T. Ahmed, and J. R. Lhota, “Reference-free interpretation of flash thermography data,” in *Proceedings of SPIE Vol. 6205*, 2006, vol. 48, no. 5, pp. 1–7.
- [2] S. M. et al. Shepard, “United States Patent: US7,186,981 B2,” US7,186,981 B2, 2007.
- [3] H. I. Ringermacher, D. R. Howard, and R. J. Filkins, “Flash-Quenching for High Resolution Thermal Depth Imaging,” in *AIP Conference Proceedings*, 2004, vol. 700, no. 1, pp. 477–481.
- [4] S. K. Everton, M. Hirsch, P. Stravroulakis, R. K. Leach, and A. T. Clare, “Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing,” *Mater. Des.*, vol. 95, pp. 431–445, 2016.
- [5] H. A. Thajeel, “Numerical modeling of infrared thermography techniques via ANSYS,” Missouri S&T, 2013.

EFFECT OF SUBSURFACE DEFECTS ON THE SURFACE TOPOGRAPHY OF ADDITIVELY MANUFACTURED COMPONENTS

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ABSTRACT

Additively manufactured (AM) components exhibit an abundance of surface textures and patterns. Past work investigating components created through laser powder bed fusion (LPBF) has shown that these patterns, specifically the chevron resulting from solidification of the melt pool on upward facing surfaces, can be correlated to quality of the final part [1]. Additionally, these patterns as well as the scan tracks have been observed to vary around the region of potential subsurface defects based on flash thermography data. This work explores parts with seeded subsurface defects at various depths from the top surface that are printed in nickel alloy 625 on a commercially available LPBF machine. Surface height maps are obtained using a scanning white light interferometer (SWLI) to determine the defect's impact on the surface texture of subsequent layers. Data obtained from the SWLI are aligned with data from X-ray computed tomography (XCT) to confirm the locations of defects and applicability of this approach as an in-situ detection method is discussed.

INTRODUCTION

Laser powder bed fusion (LPBF) is an additive manufacturing (AM) process that uses a high-power laser to selectively melt layers of metal powder. These layers are built up from an underlying substrate to form a three-dimensional structure. While the manufacturing method allows for almost unlimited design capacity, the process

itself is not without issues [2]. LPBF parts take on the order of hours or days to build, suffer from poor "as printed" surface texture, and potentially harbor unseen internal defects. This, plus the potential for part-to-part variation, inhibits the qualification and certification of AM parts for aerospace applications [2]. The internal defects, such as porosity and lack of fusion, are only found through destructive or nondestructive secondary analysis of the parts which can be costly and time consuming. Additionally, options for defect analysis become slim if one wants to keep the part intact. Flash thermography has shown some promise; however, it is limited on the depth of the defect that can be observed. X-ray computed tomography (XCT) is a viable option, but requires expertise and expensive equipment for analysis. Currently these analysis methods, both destructive and nondestructive, can only be conducted ex-situ when the part is complete, and it is far too late to remedy the defect. In-situ observation and recognition of deviations during the printing process are required if defects are to be fixed before the part is complete. Currently there is no reliable method of defect recognition during the printing process. However, understanding "as-printed" surface features may be the first step toward an in-situ method for defect detection.

Historically, these complex surfaces were being categorized by their average roughness (R_a) values alone; however, it has been shown that

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these classical parameters prove to be similar for visibly different surfaces [4-6]. This has driven a push away from using classical parameters for surface characterization. Rather, many researchers are beginning to rely on surface features to characterize metal AM parts [3-6]. In previous works, the authors have shown the connection of the chevron pattern on the top of scan lines, seen in Figure 1, to the laser parameters set for the build. A parallel study utilizing flash thermography on parts created through LBPF showed potential subsurface defects. Scanning electron microscope (SEM) images were taken at the site of the potential defect to observe any difference in surface texture. Figure 2 shows that the scan lines lose all definition in the area above the potential defect. The chevron pattern also seems to almost disappear. Upon investigation of the other potential defect sites, a pattern of flattened scan lines with no distinct boundaries emerged. In order to study this phenomenon under controlled conditions, parts with seeded defects were conceived and printed.

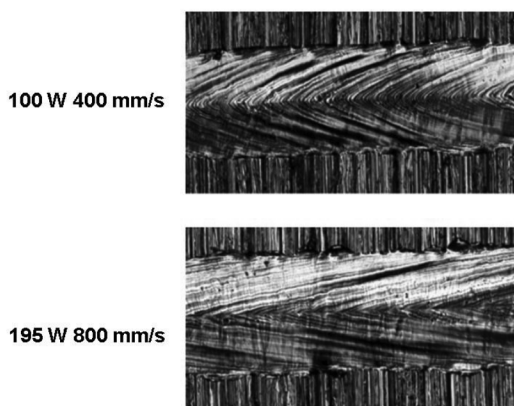


FIGURE 1. Variation in chevron pattern between different laser power and velocity combinations.

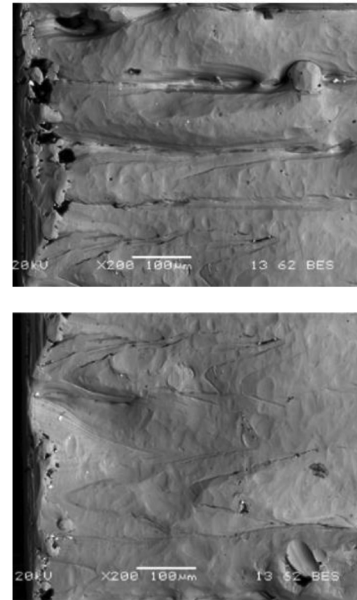


FIGURE 2. SEM image over largest potential defect (bottom). Return of scan lines away from defect (top).

Methodology

The largest hurdle in designing these parts comes in deterministically planning and creating stochastic defects. Defects are not only created in the surface through user error such as poor parameter selection, but also can occur randomly due to the chaotic nature of the printing process. The goal of the defect artifact is to encapsulate as many of these conditions in which defects can occur as possible. Three defect conditions were settled on: open hole, keyholing, and lack of fusion. Open hole defects are cylindrical areas of powder left purposely un-melted (Figure 3A). Keyhole defects were printed with the recommended laser power and half the recommended laser velocity to ensure the deposition was melting in a keyhole mode (Figure 3B). In the lack of fusion defects, the nominal hatch spacing was doubled to give subsequent printed layers issues in adhering to the defect area (Figure 3C). Defects are printed in a known grid pattern into the square artifact base. All are printed as cylinders ranging from 0.5 mm to 2.5 mm in diameter (Figure 4). The first two columns in Figure 4 (left to right) are left open to air (open air) in order to realize a local coordinate system. The rest are printed over with up to eight subsequent layers to better understand how these defects may propagate throughout a build.

The artifact is built like a staircase in that each column after the open-air defects has one more layer than the previous, and the final column is covered with eight layers (320 μm) (Figure 5). Four artifacts were printed at defect depths from two to ten layers (80 μm to 400 μm) deep to understand the size of seeded defect that could reliably be printed. All artifacts were made of nickel alloy 625 in an EOS M290 Direct Metal Laser Sintering (DMLS) machine.

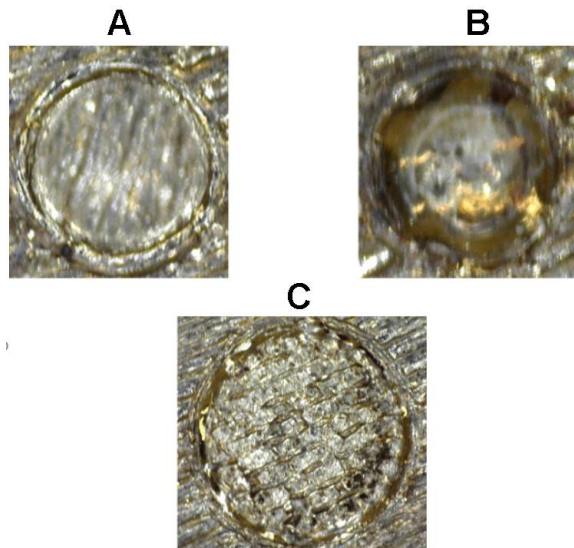


FIGURE 3. Microscope images of open-air defects A) Open hole B) Keyhole C) Lack of fusion.

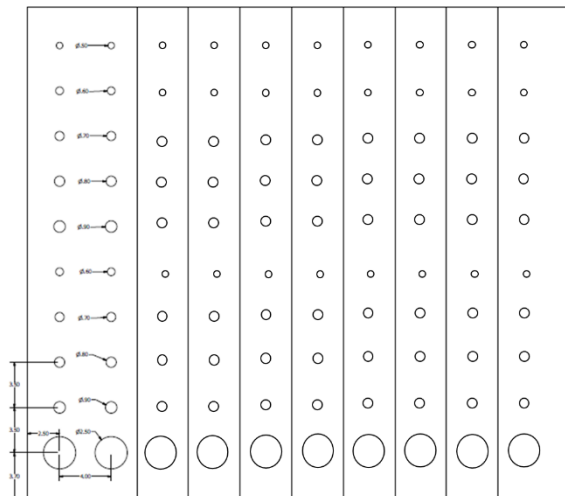


FIGURE 4. Grid pattern and size of defects in the artifact

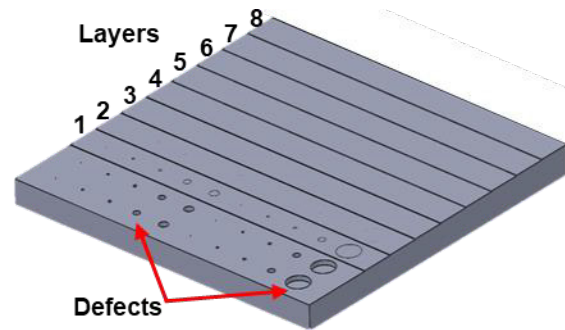


FIGURE 5. Final computer aided design model for defect artifact.

Results and Discussion

Once the artifacts were built, they were subject to X-ray computed tomography (XCT) analysis to ensure that the defects that have been printed over still exist within the part. Parts were sent to North Carolina Agricultural and Technical State University (NC A&T) for preliminary XCT analysis. It can be seen in Figure 6 that in the artifact with the deepest seeded defects (ten layers or 400 μm), all defect types are present within the surface and the largest diameter defects of each type persist throughout the entire build with up to eight layers on top.

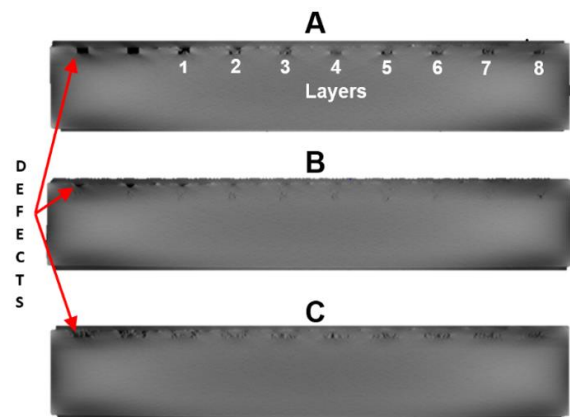


Figure 6. Defects propagating through build (0-8 layers from left to right). A) Open hole B) Keyhole C) Lack of Fusion

Areal surface data was obtained through a commercially available coherence scanning interferometer (CSI) and processed using the packaged software. To capture these defects, up to 100 sites of areal data with a field of view (FOV) of 418 μm x 418 μm were stitched together to encompass the area of the defect and outside

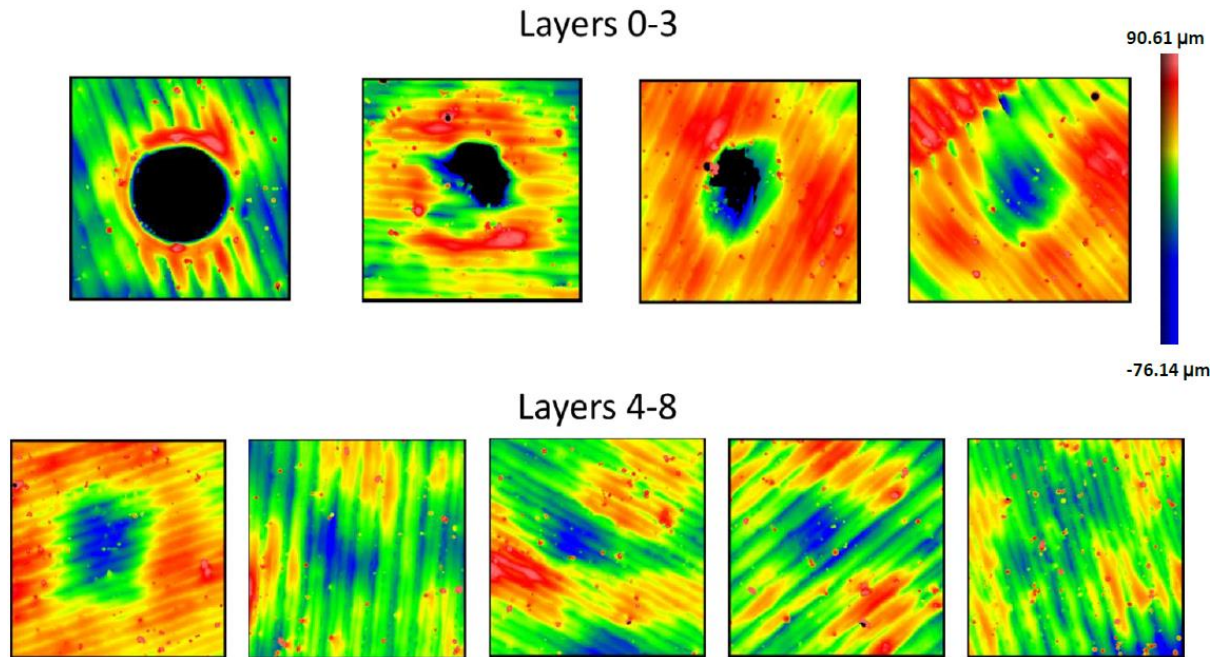


FIGURE 7. Surface topography evolution of open hole defect from 0 to 8 layers (2.25 mm x 2.25 mm FOV)

surrounding topography to view any lateral propagation that may take place as the layers are built on top of the defects. Figure 7 shows the evolution of the surface topography as the largest open hole defect goes from open air up to eight layers deep. One can see that a defect of this size takes a full three layers to fill over the defect itself. Additionally, there is a prominent sag in the spot of the defect throughout the build. At the center of this sag, it is apparent that the scan lines are losing their independence as seen in the SEM data from Figure 2. This correlates with the preliminary surface topography results found in the stochastic defect in the real-world part. The flattened scan lines are just half of the correlation between the defect artifacts and the first part analyzed. Applying a Fourier filter to the area map of the eighth layer reveals that the chevron pattern ceases to exist (Figure 8). It is theorized that the disappearance of the pattern has to do with the altered heat transfer properties of building over and around the seeded defect; however, in-depth microstructural analysis is needed to confirm this.

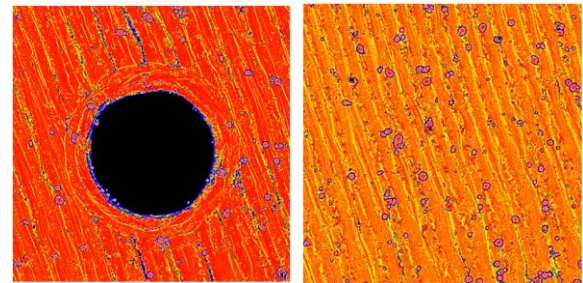


FIGURE 8. Chevron pattern adjacent to seeded defect (left). Lack of chevron pattern on eighth layer above defect

FUTURE WORK

While preliminary analysis is promising, a lot of analysis is yet to be done to prove the correlation between subsurface defects and change in the scan lines and chevron pattern seen on the upward facing surfaces. Higher fidelity XCT of defects removed from the artifact via wire electrical discharge machining (EDM) will be used to estimate the size of the initial voids as well as investigate any micro-scale porosity that may propagate throughout the part. Microstructural analysis will be completed to understand how these defects affect the expected microstructure. Finally, another series

of builds is being completed to see if the pattern holds for deeper defects (up to 30 layers).

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REFERENCES

- [1] Gockel, Joy, and Jack Beuth. "Understanding Ti-6Al-4V microstructure control in additive manufacturing via process maps." *Solid Freeform Fabrication Proceedings, Austin, TX, Aug* (2013): 12-14.
- [2] Energetics Inc. for National Institute of Standards and Technology. "Measurement science roadmap for metal-based additive manufacturing" (2013). http://www.nist.gov/el/isd/upload/NISTAdd_Mfg_Report_FINAL-2.pdf (accessed December 15, 2014).
- [3] Z. Reese *et.al.* Observations on the surface morphology of laser powder bed fusion metal surfaces. Met and Props 2017, June 2017, Gothenburg, Sweden. Unpublished conference paper, 2017.
- [4] Fox, Jason C., Shawn P. Moylan, and Brandon M. Lane. "PRELIMINARY STUDY TOWARD SURFACE TEXTURE AS A PROCESS SIGNATURE IN LASER POWDER BED FUSION ADDITIVE MANUFACTURING." *2016 Summer Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing*. 2016.
- [5] Fox JC, Moylan SP, Lane BM. Effect of process parameters on the surface roughness of overhanging structures in laser powder bed fusion additive manufacturing. *Procedia CIRP*, Charlotte, NC: 2016. doi:10.1016/j.procir.2016.02.347
- [6] Senin, Nicola, and Richard K. Leach. "Information-rich surface metrology." *Procedia CIRP* (2018).

A REVIEW OF AM ARTIFACT DESIGN METHODS

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CONTEXT

As a very promising complementary alternative to subtractive manufacturing processes, Additive manufacturing (AM) opens new perspectives and possibilities in terms of designing and manufacturing. However being in its early stage and because of the increasing number of AM systems and processes, researches are being conducted to improve, optimize and compare AM systems and processes performances with the purpose to meet a satisfying quality, both in terms of GD&T accuracy, and surface texture of asbuilt parts. One of the widely used approaches for AM systems/processes performance evaluation is measurement and characterization of printed test parts called artifacts [1] [2]. The advantage of artifacts is that for most of them they are easily measurable with existing measuring machines/techniques (there is no need to develop new measuring systems) and by building the same artifact with different AM systems/processes it is easy to compare them.

There are hundreds of artifacts designed during the last decades for AM system's performance evaluation (see *FIGURE 1*). Using artifacts for performance evaluation is neither a new practice nor unique to AM. In 2D graphic printing, tests targets are usually used for systems performance evaluation with the purpose of calibration and optimization to fit the functional requirements. Many artifacts for additive manufacturing are inspired by 2D printing test targets [2]. Also, in metal cutting machining domain, there exist several artifacts for machine characterization. One of them named circle-diamond-square stands as standard. It was developed since 1966 for performance evaluation of Computer Numerically Controlled (CNC) machining centers [1] (see *FIGURE 2*)

and has inspired the design of many artifacts for additive manufacturing.

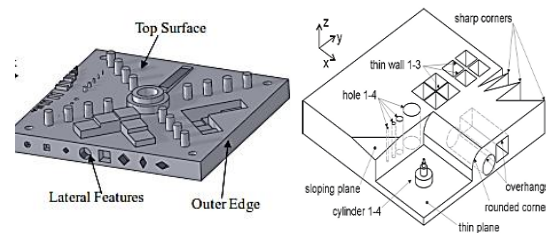


FIGURE 1. Example of AM artifacts; proposed by Moylan (left) and by Kruth (right)[3]

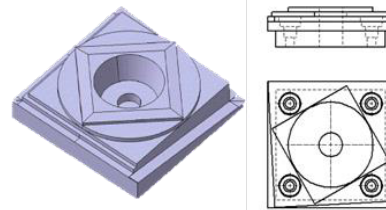


FIGURE 2. Circle-diamond-square. [1]

RESEARCH GAP

There are different papers like the recently published work of *Rebaioli et al* [3] highlighting the differences between existing AM artifacts. However, none of them explicitly examine and compare AM artifact design approaches despite the fact that the final artifact depends on the design approach, criteria and constraints definition as well as the overall design methodology.

In addition, discussing AM artifacts design methods could provide an insight into differences between final artifacts because there are different approaches for artifacts design in the literature. According to *Rebaioli et al* [3], the first and most used/common approach is based on criteria defined by *Jacobs and Richter* which focuses directly on the features of the test parts

and their shapes when defining AM design criteria and constraints. Many test parts have been designed based on this approach, others are inspired by existing artifacts in other fields (2D graphic printing, CNC, etc.). More recently, the approach proposed by the NIST in 2014 [1] has also inspired many artifacts design. Besides there are communities which randomly design artifacts and freely leave them available on websites.

PAPER'S INTEREST

In this paper focus is placed on the design of artifacts for additive manufacturing and precisely on the design methods and metrological issues. This paper presents the main existing artifacts and for each the aim is to give answers to the following questions:

- Why was the artifact designed for?
- What is the design approach?
- What are the design criteria considered?
- What are the constraints and the importance of each?
- What are the difficulties faced during the design process?

Besides GD&T accuracy evaluation, AM artifacts can be used for mechanical properties characterization (where important results are already available) and process parameters optimization/comparison (e.g. with the aim to improve the DFAM), but this paper only deals with test artifacts which characterize GD&T accuracy evaluation, repeatability and minimum feasible size/resolution of systems/processes with fit for assembly considerations.

COMMON AM ARTIFACTS DESIGN APPROACHES

Like for most products design, AM artifact design usually begins by requirements and constraints definition to be satisfied. The design process then aims to find solutions satisfying the design requirements and constraints. Thus in the literature, AM artifact design usually starts by criteria definition and each criterion is implicitly translated into design requirements. Many criteria have been defined for AM artifact design, some of them have been enhanced and completed over time. Solutions to GD&T requirements are usually represented by features (simple or complex). There are common features that repeatedly appear in the majority of existing AM artifacts.

On the other hand, a few number of AM artifacts design are based on actual parts by building them directly for AM system's performance evaluation. For instance, the first AM artifact was designed basing on real objects but the result was a limited test part unable to efficiently characterize and evaluate specific AM systems/processes characteristics and performances [3]. As previously mentioned, there are also artifacts designed basing on practices in other fields (2D printing test targets, metal cutting machining test parts).

AM Artifacts Design Criteria

There are two main tendencies in AM artifact design criteria/constraints definition. The first is to base on criteria defined by *Jacobs & Richter* and the second (and most recent) on the ones defined by *Moylan et al* [1]. As confirmed by *Rebaoli et al* [3], several artifacts have been designed according to *Jacobs & Richter's* design criteria defined as follows:

- should be large enough for performance evaluation in all the building surface (center and edges),
- should include small, medium, and large common features (cubes, thin walls, cylinders, etc.),
- features should be both positive and negative (inside and outside features),
- the test part should not be time consuming at the building stage,
- should not be material consuming,
- should be easily and quickly measurable,
- and include enough features.

These criteria have been further completed by *Byun and Lee* [4] who noted that features of an ideal artifact should also be aligned along all the axes and provide information on the minimum feasible feature/resolution of the AM system/process and by *Scaravetti et al* [5] who stated that a suitable artifact should require neither post treatment nor manual interventions (no support structures, etc.), allow evaluation of spatial repeatability and most importantly should help in linking systems/processes errors with their causes. Further, *Mehdi-Souzani et al* [6], stated that AM artifacts should also include complex features to represent complex forms achievable by AM systems/processes.

Moylan et al [1] presented a set of AM artifacts design criteria. For demonstrating

capabilities and limitations of AM systems/processes, general criteria that are not specific to systems/processes and thus not directly related to systems/processes characteristics have been defined as follows: the test part should provide information on the system's abilities to produce real world parts, also to create canonic forms (straight, circular, arced features etc.) and orientations (parallel, perpendicular and inclined features), the test part should provide information on the dimensional accuracy of the system (ability to produce features with the correct indicated size and in the correct location, the feature minimum size that can be produced) and finally, the test part should help in evaluating the system capabilities to create both cavities and bosses features. For identifying and quantifying systems errors, a number of criteria specific to powder bed fusion (PBF) systems were proposed: the test part should be designed to identify and quantify alignment errors between axis, geometric errors in laser positioning and axis positioning the building platform.

Several AM artifacts have been designed basing on previously defined design criteria. However, design constraints considered for each artifact are usually different and this can significantly affect the final test part.

AM Artifacts Design Constraints

Design constraints represent limits that must be overcome during the design process and the life circle of the product to fit the requirements/criteria. In the literature, AM artifact's design constraints are usually about measurements (system, methods, etc.) and building of the part (system characteristics, process, etc.).

Measurements constraints are usually about measurability of the test part either by one of commonly used measurement systems (contact or non-contact) or by all of them. It also concerns data collected during measurements that needs to be robust and reliable. This depends on the type of features of the artifact, their accessibility, their arrangement, the usage or not of support structures and their sizes. Hence, artifacts dimensions should avoid warping and thus prevent from a lack of result robustness by reducing the base surface largeness for instance but should be large enough to contain all the features at different dimension ranges.

Measurements constraints are also about ability of artifacts to be easily characterized by measurement standard qualification methods.

Other main design constraints are building constraints related to system/process characteristics and parameters. This is about system/process capabilities in terms of building strategy and even building surface dimensions. Another constraint is about support structures and post treatments which are usually minimized during the building of the artifact to avoid and minimize measurement errors and human intervention.

As mentioned by *Umaras et al* [7], there are errors that can be anticipated and compensated by the designer when knowing the characteristics of the intended manufacturing process during the 3D CAD test part creation such as file conversion errors (from CAD to STL, AMF, STEP, STEP NC, 3MF, VOXEL BASED format depending on the process used) which varies from one file to another. Thus, as mentioned by *Umaras et al* [7] and clearly demonstrated by *Calignano et al* [8] the destination file type can significantly affect geometric accuracy of the AM system/process depending on the file conversion parameters. This constraint is not widely considered and has been totally ignored in many test parts design [1] [5]. For instance, none of examined papers has considered file conversion errors during the design process.

TABLE 2 represents a summary of main test parts presented in this paper and for each design criteria are presented (divided into two main groups: *Jacobs and Richter* criteria and NIST's criteria) as well as design constraints and performances evaluated.

Common Features in AM Artifacts Design

As reported by *Rebaioli et al* [3], AM artifact features choice generally begins by the overall dimension definition. Knowing that artifacts should evaluate system/process accuracy within all the building surface and should be measurable by existing measuring systems, artifact's base dimensions usually take into account the building and the measurement surface dimensions in order to be replicated at different building platform locations. After that, features geometries are chosen according to the GD&T accuracy to evaluates (e.g. for flatness, choose cubes, slots, rectangular bosses, thin

walls etc.) and their dimensions defined (see TABLE 1). Simple features are likely to be used because they avoid CAO errors and reduce file conversion errors. They also allow quick visual inspection especially for form inspection.

TABLE 1. Common simple features used for AM artifacts design.

GD&T	Feature(s)
Flatness	Base surface, cube , Flat beam, slots,
Straightness (internal/external linear accuracy)	Square hole, cube, Square, Base surface, Flat beam, slots, Brackets,
Circularity (internal/external)	Cylindrical hole, cylinder
Parallelism	Square hole, square, cube,
Perpendicularity	Square hole, Square,
Angularity	Inclined feature, Brackets,
Position	Holes, cylinders
Profile	Cones, spheres, hemispheres
Surface roughness	Base surface
Cylindricity (internal/external)	Cylindrical hole, cylinder, hollow cylinders
Sphericity	Sphere
Concentricity	Cylindrical hole,
Thickness (small linear accuracy)	Wall, Hollow squares
Minimum feasible size	Fine features
Repeatability	Repeated features (e.g. Cube, cylindrical holes, spheres, cylinders)
Overhang	Flat beam

CONCLUSION AND FUTURE WORK

With focus on design criteria and constraints and also common features used in artifact design for GD&T accuracy evaluation, this paper summarizes and discusses the design methodology of existing artifacts: the most used design methodology consists in analyzing existing artifacts, highlighting the drawbacks and from that proposing a new test artifact. Some artifacts was designed using results from test targets for 2D printing systems [2], others was designed with the aim to directly assess and characterize system/process parameters.

Traditionally, to propose a new test part, features are chosen according to a set of design

criteria and arranged on a base surface. As highlighted by *Rebaioli et al* [3], there are commonly accepted criteria for artifacts design, first defined by *Jacobs and Richter*, and enhanced later. Simple geometrical features are used (cylinders, holes, wall, cones, etc.) as well as complex (freeform) features. A general method for features arrangement is proposed by *Byun and Lee* [4].

Many test parts do not consider fit for assembly criteria as well as digital chain errors constraints (more than 80% of the examined literature). This is confirmed by *Rupal et al* [9] who proposed a general methodology for fit for assembly consideration.

As previously mentioned, it also appears that by including freeform features some authors claim that, complex freeform features need to be used to totally and accurately assess AM systems/processes [6].

They are efforts to propose a standard test part for GD&T accuracy evaluation. *Moylan* [1] presented a standard test part as result of National Institute of Standard and Technology (NIST) efforts for standardization, but this test part is further criticized and modifications are proposed [3]. This is one of the reasons that motivated *Rupal et al* [9] recent work leading to the conclusion that a standard artifact is not practically advisable and it is better to think about a standard AM artifact design method. However it is necessary to say that a standard covering the definition of an artifact for the assessment of the capacity of additive manufacturing systems is being published (currently statue: "under development") [22]. This standard is resulting from a joint work of the ISO technical committee on additive manufacturing and ASTM and will be available in August 2018.

Even with this coming standard there is not yet a standard AM artifact design methodology and some artifacts are randomly designed. Thus future work should focus on proposing a detailed design methodology to help both in establishing a standard one and in designing a standard test part for AM systems/processes.

REFERENCES

- [1] Moylan S, Slotwinski J, Cooke A, Jurrens K, Donmez M A. An Additive Manufacturing Test Artifact. Journal of

- Research of the National Institute of Standards and Technology. 2014; vol. 119, DOI: 10.6028/jres.119.017.
- [2] Chang S, Li H, Ostrout N, Jhuria M. Geometric element test targets for visual inference of a printer's dimension limitations. 2015; [Online] Available: <http://scholarworks.rit.edu/other/843>.
 - [3] Rebaioli L, Fassi I. A review on benchmark artifacts for evaluating the geometrical performance of additive manufacturing processes. *Int J Adv Manuf Technol*. 2017; 93: 2571-2598, DOI: 10.1007/s00170-017-0570-0.
 - [4] Byun H-S, Lee K H. Design of a new test part for benchmarking the accuracy and surface finish of rapid prototyping processes. *International Conference on Computational Science and Its Applications—ICCSA, Springer Berlin Heidelberg*. 2003; 731–740, DOI: 10.1007/3-540-44842-X_74.
 - [5] Scaravetti D, Dubois P, Duchamp R. Qualification of rapid prototyping tools: proposition of a procedure and a test part. *Int J Adv Manuf Technol*. 2008; 38: 683-690, DOI: 10.1007/s00170-007-1129-2.
 - [6] Mehdi-Souzani C, Piratelli-Filho A, Anwer N. Comparative Study for the Metrological Characterization of Additive Manufacturing artefacts. 2016.
 - [7] Umaras E, Tsuzuki M S G. Additive manufacturing – considerations on geometric accuracy and factors of influence. *International Federation of Automatic Control*. 2017; 50: 14940-14945, DOI: 10.1016/j.ifacol.2017.08.2545.
 - [8] Calignano F, Lorusso M, Pakkanen J, Trevisan F, Ambrosio E P, Manfredi D, Fino P. Investigation of accuracy and dimensional limits of part produced in aluminum alloy by selective laser melting. *Int J Adv Manuf Technol*. 2017; 88: 451–458, DOI: 10.1007/s00170-016-8788-9.
 - [9] Rupal S B, Ahmad R, Qureshi J A. Feature-Based Methodology for Design of Geometric Benchmark Test Artifacts for Additive Manufacturing Processes. 28th CIRP Design Conference, Nantes, France. May 2018; DOI: 10.1016/j.procir.2018.02.012.
 - [10] Mahesh M, Wong Y S, Fuh J Y H, Loh H T. Benchmarking for comparative evaluation of RP systems and processes. *Rapid Prototyping Journal*. 2004; 10: 123-135, DOI: 10.1108/13552540410526999.
 - [11] Kruth J-P, Vandenbroucke B, Van Vaerenbergh J, Mercelis P. Benchmarking of different SLS/SLM processes as rapid manufacturing technique. *Int. Conf. Polymers & Moulds Innovations (PMI), Gent, Belgium*. 20-23 April 2005.
 - [12] Campanelli S L, Cardano G, Giannoccaro R, Ludovico A D, Bohez E L. Statistical analysis of the stereolithographic process to improve the accuracy. *Comput - Aided Des*. 2007; 39: 80–86, DOI:10.1016/j.cad.2006.10.003.
 - [13] Perez M A, Ramos J, Espalin D, Hossain M S, Wicker R B. Ranking model for 3D printers. *Proceedings of the 24th Annual International Solid Freeform Fabrication Symposium, Austin (TX), USA*. 2013; 1048-1065.
 - [14] Jared B H, Tran H D, Saiz D, Boucher C L, Dinardo E. Metrology for additive manufacturing parts and processes. Presented at Spring Topical Meeting 57. 2014.
 - [15] Hao B, Korkmaz E, Bediz B, Ozdoganlar O B. A novel test artifact for performance evaluation of additive manufacturing processes. Presented at American Society for Precision Engineering Conference. 2014.
 - [16] Sanchez F A C, Boudaoud H, Muller L, Camargo M. Towards a standard experimental protocol for open source additive manufacturing. *Virtual and Physical Prototyping*. 2014; 9: 151–167, DOI: 10.1080/17452759.2014.919553.
 - [17] Yang L, Anam M A. An investigation of standard test part design for additive manufacturing. *Proceedings of the 25th Annual International Solid Freeform Fabrication Symposium, Austin (TX), USA*. 2014; 901-922.
 - [18] Thompson M K, Mischkot M. Design of test parts to characterize micro additive manufacturing processes. 9th International Conference on Axiomatic Design – ICAD. 2015; 223-228, DOI: 10.1016/j.procir.2015.07.065.
 - [19] Islam M N, Sacks S. An experimental investigation into the dimensional error of powder-binder three-dimensional printing. *Int J Adv Manuf Technol*. 2016; 82: 1371-1380, DOI: 10.1007/s00170-015-7482-7.
 - [20] Islam M N, Gomer H, Sacks S. Comparison of dimensional accuracies of stereolithography and powder binder

printing. Int J Adv Manuf Technol. 2016; 1–11, DOI: 10.1007/s00170-016-8988-3.

- [21] Yang H, Lim J C, Liu Y, Qi X, Yap Y L, Dikshit V, Yeong W Y, Wei J. Performance evaluation of ProJet multi-material jetting 3D printer. Virtual and Physical Prototyping. 2016; DOI: 10.1080/17452759.2016.1242915.

- [22] ISO/ ASTM DIS 52902 (ASTM F42)-August 2018 - Additive manufacturing-test artefacts - Standard guideline for geometric capability assessment of additive manufacturing systems.

TABLE 2. An overview of test parts design approaches for GD&T accuracy evaluation. Design criteria from C1 to C5 respectively refer to Richter & Jacobs criteria, Moylan's (NIST) criteria, features orientation along the system's axes, linking errors to their causes and usage of enough free-forms features. Design constraints Co1, Co2 and Co3 respectively represent system's/process parameters constraints, file conversion errors and measurement constraints. MFS stands for Minimum Feasible Size evaluation while Rep is for Repeatability evaluation.

Author (s)	Year	Design approach									Size level			GD&T	MFS	Rep	Process
		criteria					constraints										
		C1	C2	C3	C4	C5	Co1	Co2	Co3	Micro	Meso	Macro					
Buyn and Lee [4]	2003	X		X			X		X		X		X	X			SL
M. Mahesh et al [10]	2004	X					X		X		X		X	X	X		SL, SLS FDM, LOM
J.-P. Kruth et al [11]	2005	X			X		X		X	X	X		X	X			SLS, SLM
S. L. Campanelli et al [12]	2007	X					X		X		X		X				SL
D. Scaravetti et al [5]	2008	X		X	X		X		X		X		X		X		SL
M. A. Perez et al [13]	2013	X		X			X		X		X		X				LOM
S. Moylan et al [1]	2014	X	X	X			X		X		X		X	X			BJ, FDM, SLS, SLM, EBM
B. H. Jared et al [14]	2014	X	X				X		X		X		X	X			
B. Hao et al [15]	2014	X		X		X	X		X	X	X		X	X	X		MJ
F. A. C. Sanchez et al [16]	2014	X	X	X	X		X		X		X		X				FDM
L. Yang and M.A. Anam [17]	2014	X	X	X	X		X		X				X	X			SLS
S. Chang et al [2]	2015	X		X			X		X		X		X				FDM
M. K. Thompson et al [18]	2015	X					X		X	X					X	X	SL
M. N. Islam et al [19]	2016	X					X		X	X			X				BJ, MJ
H. Yang et al [21]	2016	X	X	X			X		X	X			X	X	X		MJ
C. Mehdi-Souzani et al [6]	2016	X	X			X	X		X		X		X				Powder binder process

BENCHMARKING OF AN ADDITIVE MANUFACTURING PROCESS

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INTRODUCTION

To accurately assess the performance of an additive manufacturing (AM) system, an analysis of its building capabilities is needed. In this paper, a benchmarking artefact for AM quality testing is measured following established methods. The use of benchmarking artefacts to test AM systems has been the subject of previous work [1], but these studies usually lack a deep metrological analysis. The measurements that we provide are obtained with three different systems: a contact coordinate measuring machine (CMM), a non-contact photogrammetry system (PG) and an X-ray computed tomography system (XCT). The benchmarking artefact (figure 1) was designed for a powder bed fusion AM process [2]; in particular, high-speed sintering (HSS) [3]. HSS is a powder bed fusion process in which a polymer is sintered by an infrared lamp with the aid of an infrared-absorbing jetted ink. The HSS process provides freedom of design and does not need supports structures. The measurement results of the benchmarking

artefact provide information about the performance of the AM system through the analysis of basic benchmarking features: sphericity, cylindricity, parallelism, coaxiality, minimum feature dimensions and build angles.

Design-for-metrology is a methodology in development at the University of Nottingham, aiming to improve and facilitate measurements of AM parts. Design-for-metrology ensures that the characteristics, limitations and standard procedures of available measurement systems are taken into account at the component design stage [2]. The necessity for this methodology comes from the increased complexity of AM parts compared with traditionally manufactured parts. AM parts often include internal features, lattice structures, cavities and freeform geometries which present serious challenges for current metrology systems [4]. Complementing this methodology development, new metrology systems are being developed at the University of Nottingham to overcome these challenges [5].

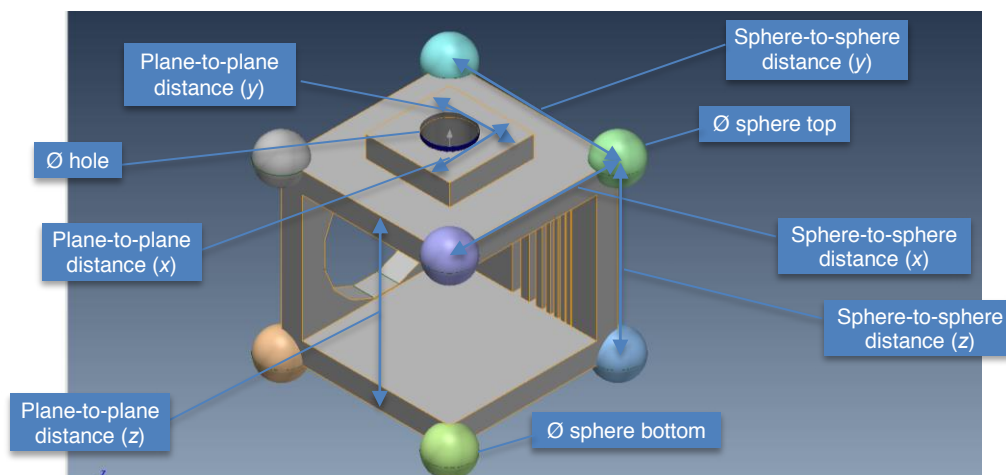


FIGURE 1. CAD model of the artefact with some of the features analysed in this paper highlighted.

A benchmarking artefact was previously designed for use with an HSS system. The artefact was created to test the system performance due to the absence of an industrial standard benchmark for AM machines. The artefact consists of a hollow cube with a side length of 40 mm, featuring spheres of 5 mm radius at each vertex. Each face of the cube possesses a range of features to provide information about the AM system: parallel planes, holes, cylinders, features of decreasing dimension, inclined planes and spheres.

MEASUREMENTS

Contact CMM

A traceable CMM at the National Physical Laboratory (NPL) was used to measure the artefact. The reliability and standardisation of CMMs make them ideally suited to provide a traceable dataset for comparison with other measurement systems. CMMs tend to be slower than other methods, as well as register a low number of points. Measurement time is another factor to consider, with high detailed planning of the measurement being necessary as well as the slow point acquisition.

The CMM used was a Mitutoyo Crysta S Apex 776, with a 55 mm long, 1 mm diameter ball-tipped stylus, and a probing deflection of 0.2 mm. Measurements were made in a temperature-controlled laboratory at $(20 \pm 2)^\circ\text{C}$. The CMM had a maximum permissible measuring error $E_0 = 1.7 + 3L \mu\text{m}$ (where L is the test length in millimetres) and a maximum permissible probing error $P_{FTU} = 1.7 \mu\text{m}$ [6]. The uncertainty simulations of the CMM measurements were carried out using PUNDIT CMM5 software [7]. For the uncertainty simulations, the following parameters were added to the model: a measured temperature of $(20 \pm 1)^\circ\text{C}$, a linear coefficient of thermal expansion (assumed) $\alpha = (8 \pm 1) \times 10^{-5} \text{ K}^{-1}$ and a mean roughness depth, R_z of $25 \mu\text{m}$, $50 \mu\text{m}$ and $75 \mu\text{m}$. More than one value of R_z was tested to better understand the importance of roughness on the uncertainty calculation. The roughness R_z was measured at Nottingham with a contact stylus instrument, with a value of $(50 \pm 3) \mu\text{m}$. The CMM measurements with uncertainty statements help to assess the reliability of the measurements against the resolution of the AM system.

Photogrammetry

Photogrammetry is a measurement technology based on the triangulation of points from many images. The expanded uncertainties [8] of $20 \mu\text{m}$ that photogrammetry can achieve is generally larger than CMMs (usually with maximum permissible errors lower than $10 \mu\text{m}$), but photogrammetry can provide high density point clouds for complex AM parts at relatively high speeds. Additionally, the observable texture on samples produced by the HSS system produces strong correspondence between images, allowing high-density point clouds to be produced. Despite time-consuming reconstruction algorithms, high-speed data acquisition makes the measurement process faster and cheaper than the other two methods provided here (CMM and XCT). Photogrammetry measurements were made in a temperature-controlled laboratory at $(20 \pm 0.5)^\circ\text{C}$ at the University of Nottingham. The scaling factor for the point cloud was obtained using the distance between centres of spheres obtained with the CMM, due to its low uncertainty, $0.006 \mu\text{m}$. The uncertainty of the scaled reconstruction was then evaluated using a combination of the CMM uncertainty and sphere to sphere uncertainties evaluated in previous work [8].

X-ray computed tomography

X-ray computed tomography (XCT) is a measurement technique that uses X-rays to produce volumetric representations of an object [9]. The main advantage of XCT compared to other measurement techniques is its ability to detect the internal features of a component non-destructively. Although typically more expensive than the other options presented, XCT is the only way to obtain measurements for the most complex AM geometries. XCT is also typically more time-consuming than other non-contact measurement methods due to the high number of projections needed for the measurements. XCT is also able to provide internal defect and porosity information of AM parts. The XCT system used here was a Nikon MCT 225, with a quoted maximum permissible error, $MPE = 9 + L/50 \mu\text{m}$ (where L is the test length in millimetres) and a temperature-controlled cabinet at $(20 \pm 0.1)^\circ\text{C}$, which is itself in a temperature-controlled laboratory at $(20 \pm 0.5)^\circ\text{C}$. Due to the high complexity of the XCT system, measurements are provided with an uncertainty analysis comprising an addition in quadrature of the MPE and the statistical experimental uncertainty.

The following parameters were used for XCT measurement: voltage 110 kV, current 318 μ A, 3142 projections, exposure 2 s and gain 24 dB. A detector shading correction was applied by averaging 256 reference frames (128 bright and 128 dark) and a warmup scan of approximately one hour was performed prior to a batch of three repeated scans. A 0.75 mm copper pre-filter was used between the X-ray source and the artefact. X-ray imaging and volumetric reconstruction were performed using the manufacturer's proprietary software (X-Inspect and CT-Pro, respectively), using the FDK algorithm [10] with a first order beam hardening correction and a Ramp noise filter, with cut-off at the maximum spatial frequency. Following reconstruction, XCT data were imported into Volume Graphics VGStudioMAX 3.0 [11] and surfaces were determined using the local maximum gradient algorithm over a search distance of four voxels, beginning from the ISO 50 % isosurface [12].

RESULTS AND DISCUSSION

Calculations of the uncertainty of the CMM measurements were made for different roughness values (see Table 1, where the uncertainty values of the sphere diameters are shown). The uncertainty calculations of the CMM measurements showed a high dependence of the surface roughness characteristic of AM parts. Previous research shows values of R_z between 30.78 μ m and 74.99 μ m for a selectively laser sintered polyamide [13], so 25 μ m, 50 μ m and 75 μ m values of R_z where used for the uncertainty calculations, with the aim of having a better indication of the CMM measurements uncertainty of the of the process under different printing parameters.

TABLE 1. *Uncertainty values for a 10 mm diameter sphere obtained for the CMM measurements with variations on the R_z*

R_z (mm)	Uncertainty of a 10 mm $\varnothing$ sphere (mm)
0.025	0.03
0.050	0.05
0.075	0.08

The measurements of the external diameters are larger on the CMM than the XCT and the photogrammetry systems, while the internal diameters are measured smaller (see Table 2). All these measurements had a nominal value on the CAD model of 10 mm. The measurements follow the systematic difference between XCT and contact CMM shown elsewhere [14], where the measured external diameter of a cylinder on an XCT system is smaller than the CMM measurement by approximately $R_z/2$, while internal diameters are larger than CMM values by $R_z/2$.

TABLE 2. *Measurements for the sphere, cylinder and hole diameter features.*

Feature	XCT (mm)	CMM (mm)	PG (mm)
$\varnothing$ sphere top	9.896 $\pm$ 0.019	10.22 $\pm$ 0.05	10.05 $\pm$ 0.04
$\varnothing$ sphere bottom	9.911 $\pm$ 0.019	10.28 $\pm$ 0.05	9.98 $\pm$ 0.04
$\varnothing$ hole	10.04 $\pm$ 0.02	9.99 $\pm$ 0.05	10.09 $\pm$ 0.04
$\varnothing$ cylinder	9.94 $\pm$ 0.02	9.94 $\pm$ 0.05	9.94 $\pm$ 0.04

The linear distance between spheres centres (see table 3) allows a better understanding of the dimensional precision of the AM system, due to their low uncertainties and better measurement precision. The system shows a slight shrinkage in the horizontal plane (the CAD model has a 40 mm distance between spheres centres) and an expansion along the z axis. The shrinkage in the horizontal plane is not affected by the direction, so its cause is not directly related to the inkjetting process or the machine movement. The plane-to-plane distances show a larger difference compared to the CAD values than the sphere-to-sphere distance. This originates from the high surface roughness resulting from the HSS process. In the plane-to-plane distance, the photogrammetry results show a higher value than the other two measurement methods, and its precision decays greatly with the increase of the distance measured.

TABLE 3. Results for the plane-to-plane and sphere-to-sphere distance of the different measurement instruments.

Feature	XCT (mm)	CMM (mm)	PG (mm)
Plane-to-plane distance (x)	19.89 ± 0.02	19.88 ± 0.06	19.93 ± 0.04
Plane-to-plane distance (y)	19.923 ± 0.019	19.93 ± 0.05	19.99 ± 0.04
Plane-to-plane distance (z)	39.86 ± 0.02	39.98 ± 0.05	40.02 ± 0.04
Sphere-to-sphere distance (x)	39.943 ± 0.019	39.947 ± 0.006	39.95 ± 0.04
Sphere-to-sphere distance (y)	39.929 ± 0.019	39.947 ± 0.006	39.96 ± 0.04
Sphere-to-sphere distance (z)	40.09 ± 0.02	40.109 ± 0.006	40.13 ± 0.04

CONCLUSIONS

The results provide information about the performance of the HSS system, helping to establish operating parameters for the process. They also demonstrate the effectiveness of the benchmarking artefact design. The spheres that the artefact provide allow for effective comparison between different measurements systems. The results show the high dependence on surface roughness on the uncertainty values for the CMM. These uncertainty values are relatively large in comparison with other traditional manufacturing processes such as machining. Those high uncertainties can difficult the use of AM parts for precision applications. To overcome this obstacle, improvements either on the measurements or on the printing processes are needed, Uncertainty values are lower on the non-contact systems for the measurement of features other than the sphere-to-sphere distances, but standardisation has not been provided, so their use on industrial applications should be used with caution. The results show that CMM may not be the most effective system for the reference measurement of AM parts, and non-contact systems maybe be more adequate.

REFERENCES

- [1] Rebaioli L, Fassi I. A review on benchmark artifacts for evaluating the geometrical performance of additive manufacturing processes. *International Journal of Advanced Manufacturing Technology*. 2017; 93: 2571–2598.
- [2] Rivas Santos VM, Sims-waterhouse D, Piano S, et al. Metrological design of calibration and benchmarking artefacts for an additive manufacturing system. *Dimensional Accuracy and Surface Finish in Additive Manufacturing*. Leuven, 2017; 24–27.
- [3] Ellis A, Noble CJ, Hopkinson N. High Speed Sintering: Assessing the influence of print density on microstructure and mechanical properties of nylon parts. *Additive Manufacturing*. 2014; 1–4: 48–51.
- [4] Thompson MK, Moroni G, Vaneker T, et al. Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals - Manufacturing Technology* 2016; 65: 737–760.
- [5] Stavroulakis PI, Chen S, Sims-Waterhouse D, et al. Combined use of a priori data for fast system self-calibration of a non-rigid multi-camera fringe projection system. *Modeling Aspects in Optical Metrology VI*. Munich, 2017; 1033006.
- [6] ISO. 10360 Geometrical product specifications (GPS) Acceptance and reverification tests for coordinate measuring machines (CMM). 2009.
- [7] Beaman J, Morse E. Experimental evaluation of software estimates of task specific measurement uncertainty for CMMs. *Precision Engineering*. 2010; 34: 28-33.
- [8] Sims-Waterhouse D, Piano S, Leach R. Verification of micro-scale photogrammetry for smooth three-dimensional object measurement. *Measurement Science and Technology*. 2017; 28: 55010–16.
- [9] Thompson A, Maskery I, Leach RK. X-ray computed tomography for additive manufacturing: a review. *Measurement Science and Technology*. 2016; 27: 72001–18.
- [10] Hermanek P, Sing J, Rathore, et al. Principles of X-ray Computed Tomography. *Industrial X-ray computed*

- tomography. Springer, New York: 2017; 25–68.
- [11] Volume Graphics. VGStudio MAX.
 - [12] Kiekens K, Welkenhuyzen F, Tan Y, et al. A test object with parallel grooves for calibration and accuracy assessment of industrial computed tomography (CT) metrology. *Measurement Science and Technology*. 2011; 22: 115502.
 - [13] Sachdeva A, Singh S, Sharma VS. Investigating surface roughness of parts produced by SLS process. *International Journal of Advanced Manufacturing Technology*. 2013; 64: 1505–1516.
 - [14] Aloisi V, Carmignato S. Effect of surface roughness on uncertainty of X-ray CT dimensional measurements of additive manufactured parts. *Case Studies in Nondestructive Testing and Evaluation*. 2015; 6: 104–106.

SELECTIVE LASER MELTING: THE USE OF METROLOGY TO ASSURE PROCESS INTEGRITY

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INTRODUCTION

Selective Laser Melting (SLM) provides the capability to produce complex geometrical shapes and innovative weight reducing parts. Currently, however, there is a need to confirm that the parts being produced are acceptable because the process cannot be fully assured. This is a challenge to companies wishing to use parts constructed via this manufacturing process for safety-critical components.

Measurement can lead to improvement, so post-process monitoring can provide valuable information to the research regarding the capability of the SLM process which is currently largely unknown. Some studies have introduced possible designs of a test artefact that can allow the evaluation of the ALM process capability in terms of geometrical and mechanical accuracy. These test artefacts need to be designed and include features with measurements that will indicate whether the process performs to the required accuracy and precision (1).

This paper considers the use of a Co-ordinate Measuring Machine (CMM), fitted with the Renishaw REVO 5-axis probing system in artefact quality assessment. The CMM is deployed to measure a test piece consisting of seven cylinders with specified dimensions, shown in Figure 1. In this initial investigation a sequence of repeatable and reproducible cycles are enacted using the specified artefact. Following the verification of the suitability of the experimental set-up and procedure, sets of twelve test pieces, with known locations and orientations were measured and assessed. The test pieces are then measured to identify the occurrence of variation across a build plate. This is repeated following production, post heat treatment and removal from the build plate. The

information is then used to evaluate the process outputs to assure product integrity.

METHOD

A test piece, called the 'Top-hat', was designed with the aim of examining changes in process quality across the build platform. The test piece consists of seven cylinders of 6mm diameter positioned in a row. The depths of the cylinders vary from 5.82 to 6.18 mm and the centre of each cylinder is located 10 mm away from the adjacent cylinder. The drawing of the test piece is shown in Figure 1 indicating the dimensions and tolerances of interest. The location of the twelve Top-hat assemblies on the build plate are shown in Figure 2.

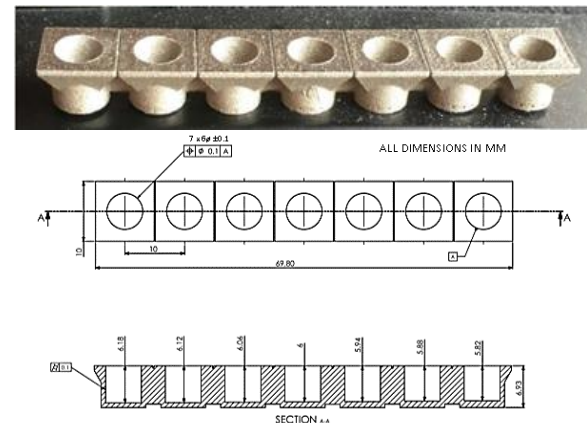


FIGURE 1. (Top): Top-hat assembly removed from build plate, (Bottom): CAD drawing of Top-hat assembly (test piece).

The Top-hats were produced using an AM250 Renishaw selective laser melting machine (SLM) shown in Figure 3. This employs a modulated ytterbium fibre laser with a wavelength of 1.071nm, the nominal diameter of the focussed laser spot is 75µm. The laser employed uses discrete point exposures instead of running continuously. To create the Top-hats, the laser beam traces the Top-hat geometry onto the

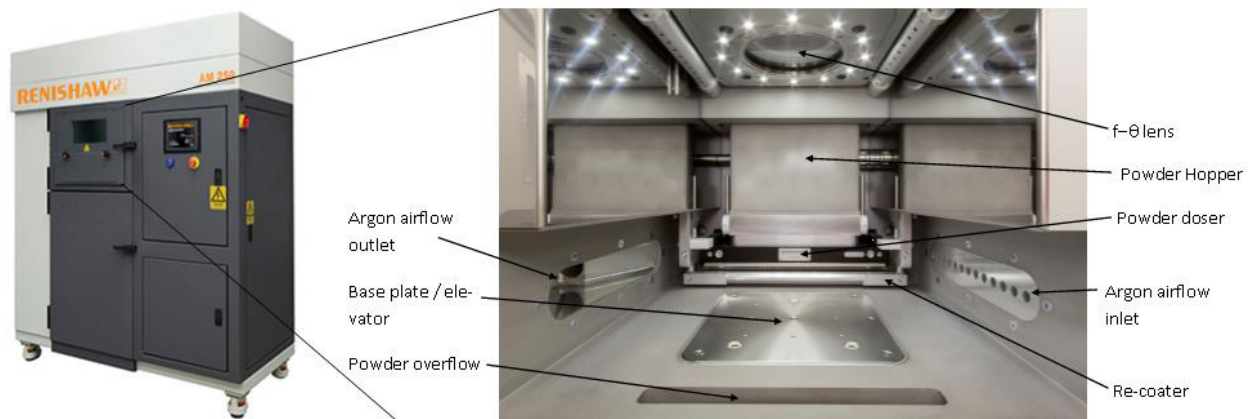


FIGURE 3. AM250 & build chamber.

powder layer. The energy from the laser is absorbed through radiation by the powder and the heat transfer produces a phase transformation. The powder changes from a solid to a liquid, forming a melt pool. Once the laser moves, this melt pool solidifies to produce a consolidated layer. When the scan finishes the geometry for the layer, the build bed is lowered and a fresh layer of powder is deposited. The process will then be repeated until the end of the build program and the part is finished. The scanning strategy employed for this study was meander, with a rotation angle between each adjacent layer of 67° to eliminate the chance of scan lines repeating themselves directly on top of each other as represented in Figure 4. Table 1 provides the machine set up information used to produce all the parts on the plate.

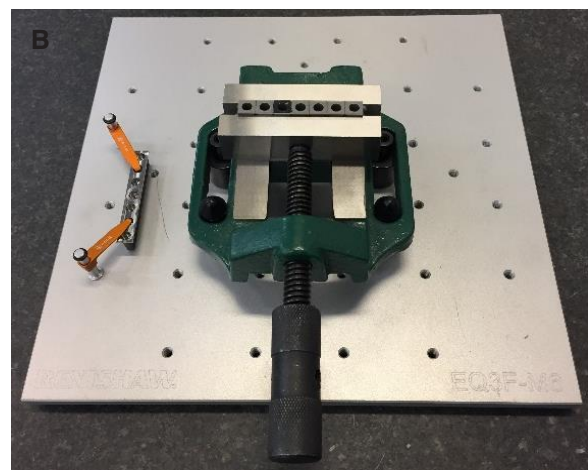


FIGURE 2. 12 stainless steel Top-hat assemblies on build plate (A). Top-hat from plate 5 position 12 in machine vice with specific grips (B).

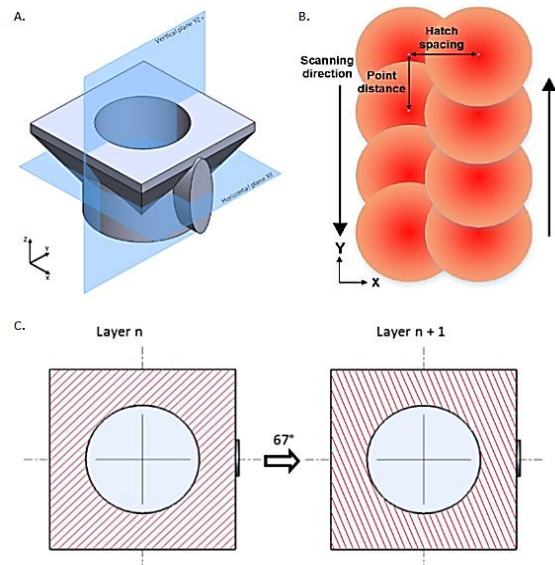
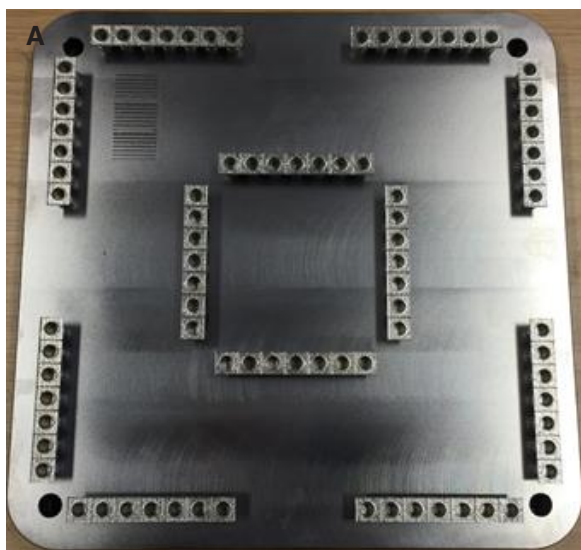


FIGURE 4. Schematic of (A) section laser strategy for a Top-hat; (B) laser working mode; (C) laser scanning strategy for multiple layers.

TABLE 1. SLM part production settings.

Parameter	Value/Setting	Units
Layer thickness	50	μm
Shrinkage XY	-	%
Shrinkage Z	-	%
External support parameters		
Speed	150	mm/s
Power output	200	W
Focus offset	0	mm
Point distance	50	μm
Exposure time	90	μs
Meander-30 hatch style		
Layer path organisation	Inside to outside	
Volume border		
Speed	150	mm/s
Power output	110	W
Focus offset	0	mm
Point distance	20	μm
Exposure time	100	μs
Volume offset hatch		
Speed	150	mm/s
Power output	200	W
Focus offset	0	mm
Point distance	60	μm
Exposure time	80	μs
Volume area		
Speed	150	mm/s
Power output	200	W
Focus offset	0	mm
Point distance	85	μm
Exposure time	80	μs
Spot compensation	0.035	mm
Volume offset		
hatch offset space	0.0	mm
Volume area		
hatch space	0.11	mm
contour space	0.09	mm

Once manufactured, the Top-hat assemblies were measured in three varying states; parts on the plate pre-heat treatment, parts on the plate post-heat treatment and parts removed from the plate, heat treated. Figure 1 shows the Top-hat assembly once it has been removed from the build plate. All the plates manufactured underwent the same heat treatment process. The plates were heated to 1050-1120°C, held for an hour and cooled to room temperature under inert conditions using Argon. Figure 4 indicates the scans and touch points measured using the CMM in this study. The cylinder was measured using three different techniques. The first employed three scanned sweeps around the circumference of the bore at three different

heights. The second completed the same process but took nine individual point touches around the internal bore at three different heights. The last used a helix sweep to scan the inside of the bore of the cylinder starting and stopping 1mm from the bottom and the top. The top plane and the bottom of the cylinder were measured using a number of touch points. To execute this operation a 2mm ruby probe was utilised. This was carried out in the Metrology laboratory in Cardiff University. This laboratory is environmentally controlled and the measurements were taken at a temperature of 23°C. The number of touch points and scan points were derived following (2) and (3).

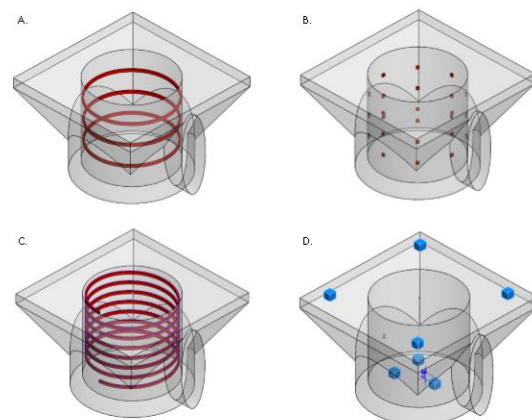


FIGURE 4. One SLM manufactured Top hat section showing CMM touch points and scans. (A): Top-Hat defined with three circular sweeps set at different heights; (B): Top hat with cylinder defined with touch points; (C): Top hat with cylinder defined with helix sweep; (D): Top hat planes defined with touch points on the top surface and bottom of cylinder.

The CMM needs to be capable of measuring the test pieces. Therefore, before completing a gauge repeatability and reproducibility (Gauge R&R) study the resolution of the gauge needs to be assessed. The measurement system must have a resolution (RE) of $\%RE \leq 5\%$ of the characteristics specified tolerance in order to be able to reliably determine and observe measurement values. The measurement deemed important in this study is the diameter of the cylinders which have a nominal diameter dimension = $6\text{mm} \pm 0.1\text{mm}$. The specified tolerance (RF) for the cylinder is 0.2mm so 5% is equivalent to 0.01mm, the resolution of the CMM is 0.0001mm as stated by (Mitutoyo Euro Apex

and Renishaws REVO 5-axis head) %RE is calculated as 0.05% by Equation (1);

$$\%RE = \frac{RE}{RF} * 100 \quad (1)$$

The %RE is < 5%, therefore the CMM has the appropriate resolution to measure the test pieces. As no mechanical device is perfect, the measurement uncertainty also needs to be considered. The standard uncertainty calculated based on maximum permissible error (u_{MPE}) is calculated from (4) Equation (2):

$$u_{MPE} = \frac{M_{PE}}{\sqrt{3}} \quad (2)$$

Equation (3) considers only the uncertainty in the CMM and not the environment the machine is in. Therefore, only the uncertainty measurements applicable were taken from the calibration certificate (5). In this equation only the MPE (E0X), MPE (E0Y) and MPE (E0Z) uncertainties were used because of how the measurements in the study were acquired. MPE (E0X) = 0.0396, MPE (E0Y) = 0.0396 and MPE (E0Z) = 0.0396.

$$u_{MPE} = \sqrt{\frac{M_{PE1}^2}{3} + \frac{M_{PE2}^2}{3} + \frac{M_{PE3}^2}{3}} \quad (3)$$

$$u_{MPE} = \sqrt{\frac{0.0396^2}{3} + \frac{0.0396^2}{3} + \frac{0.0396^2}{3}}$$

$$u_{MPE} = 0.0237\mu m$$

Gauge type-1 study can be used to assess the repeatability and bias of the measurement system in use, suggesting that one operator performs the measurement of a single part multiple times. Once the data is collected; measurement system capability indices C_g and C_{gk} can be calculated. C_g reflects the repeatability of the measurements while C_{gk} reflects both repeatability and bias from the true value (6). The diameter Bias (Bi) for CLY001 is calculated using Equation (4) where the average measurement value ($\bar{x}_g$) repeatability standard deviation (x_m) is taken from Table 2.

$$Bi = |\bar{x}_g - x_m| \quad (4)$$

$$\bar{x}_g = 5.798mm$$

$$x_m = 6mm$$

Therefore:

$$Bi = |5.794 - 6|$$

$$Bi = -0.206$$

As this study is not looking at the capability of the manufacturing process, the target and bias shown above can be ignored. It is important to point out though, that the bias will need to be explored and explained.

Removing systematic errors leaves the capability index C_g , Equation (5). This is used to assess the repeatability of the measurements, considering only the spread of the measurements and not the bias. For example, the upper and lower specification limits for the diameter are 5.9 mm and 6.1 mm respectively. However, the acceptable measurement tolerance is 0.04mm calculated as 20% of the part tolerance for diameter which is 0.2 mm. The measurements will still be considered as repeatable if the variation is within 0.04 mm even if the measurement mean is biased. The capability index C_g will indicate how well the spread of the repeated measurements fit into the specified spread. Using the measurements from Table 2, capability index C_g for cylinder 1 is calculated as follows:

$$C_g = \frac{0.2 * T}{4 * S_g} \quad (5)$$

$$C_g = 33.33 > 1.33 \therefore \text{acceptable}$$

C_g was also calculated for true position, diameter, cylindricity, top plane, bottom plane and the depths of each of the seven cylinders of the test piece. The results are shown in Table 3. Results for C_g less than or equal to 1.33 are indicated in red, results greater than 1.33 are indicated in green.

Table 3 shows that the diameter, cylindricity, top plane, bottom plane and depth are all repeatable to 20% (40 μm) of the feature tolerance. The diameter and depth are also repeatable to 5% (10 μm) of the feature tolerance. The true position is not repeatable to 20% (20 μm) of the feature tolerance when the part has been removed from the plate.

TABLE 2. Gauge study results, Plate 5 position 12c – All diameters (mm)

Trial	CYL001	CYL002	CYL003	CYL004	CYL005	CYL006	CYL007
1	5.794	5.799	5.801	5.794	5.799	5.796	5.8035
2	5.794	5.799	5.8	5.794	5.799	5.797	5.8036
3	5.795	5.799	5.8	5.794	5.799	5.797	5.8035
4	5.794	5.799	5.801	5.794	5.799	5.796	5.8035
5	5.794	5.799	5.801	5.794	5.799	5.796	5.8035
6	5.794	5.799	5.801	5.794	5.799	5.797	5.8035
7	5.794	5.799	5.801	5.793	5.798	5.797	5.8036
8	5.795	5.799	5.801	5.794	5.799	5.797	5.8034
9	5.794	5.799	5.801	5.794	5.799	5.797	5.8034
10	5.794	5.798	5.801	5.794	5.799	5.797	5.8036
11	5.794	5.799	5.801	5.794	5.799	5.797	5.8035
12	5.794	5.799	5.801	5.794	5.799	5.797	5.8034
13	5.794	5.798	5.801	5.794	5.799	5.796	5.8036
14	5.794	5.799	5.801	5.794	5.799	5.797	5.8035
15	5.794	5.798	5.801	5.794	5.799	5.796	5.8035
16	5.794	5.798	5.801	5.794	5.799	5.797	5.8035
17	5.794	5.799	5.801	5.794	5.799	5.796	5.8035
18	5.794	5.799	5.801	5.794	5.799	5.797	5.8034
19	5.794	5.799	5.801	5.794	5.799	5.797	5.8036
20	5.794	5.798	5.801	5.794	5.799	5.797	5.8035
21	5.794	5.798	5.801	5.794	5.798	5.797	5.8035
22	5.794	5.799	5.801	5.794	5.799	5.797	5.8034
23	5.794	5.798	5.801	5.794	5.798	5.797	5.8034
24	5.794	5.798	5.801	5.794	5.798	5.796	5.8036
25	5.794	5.799	5.801	5.794	5.799	5.796	5.8036
Mean	5.794	5.799	5.801	5.794	5.799	5.797	5.804
Range	0.001	0.001	0.001	0.001	0.001	0.001	0.000
St Dev	0.0003	0.0005	0.0003	0.0002	0.0004	0.0005	0.0001

TABLE 3. Cg values – Plate 5 Position 12c

	True position	Diameter		Cylindricity	Top Plane		Bottom Plane		Depth Difference	
T	0.1	0.2		0.1	0.2		0.2		0.2	
P%	20%	20%	5%	20%	20%	5%	20%	5%	20%	5%
CYL001	1.24	33.33	5.56	2.69	15.31	2.55	36.12	6.02	17.32	2.89
CYL002	0.90	20.00	3.33	1.92	14.48	2.41	32.49	5.41	19.13	3.19
CYL003	0.99	33.33	5.56	2.08	9.95	1.66	9.81	1.63	21.00	3.50
CYL004	1.10	50.00	8.33	2.73	6.17	1.03	6.65	1.11	13.40	2.23
CYL005	1.08	25.00	4.17	2.63	5.66	0.94	4.91	0.82	22.00	3.67
CYL006	0.93	20.00	3.33	2.57	4.29	0.71	3.91	0.65	21.00	3.50
CYL007	1.67	100.00	16.67	5.11	3.40	0.57	3.14	0.52	20.00	3.33

Gauge repeatability and reproducibility (GR&R) study using ISO 12888:2011 was completed to identify the contributing factors for each measured feature. Each Top-hat section was considered as a separate part (seven parts) and

measured three times by three different operators. The acquired results are depicted in Figure 5 and Tables 4, 5 and 6. It can be seen that the major source of variation is part-to-part.

The reproducibility and interaction between the part and operator were insignificant. As seen in Table 6, the measurement system variance takes up 1.21% of the total variance, of which repeatability is 1.21% and reproducibility is 0%. The interaction between the part and the

operator has been removed (Table 5) because the p-value is greater than 5%. This is due to the data set being too small. There is not enough data in this study to tell if the means of the three data sets are the same.

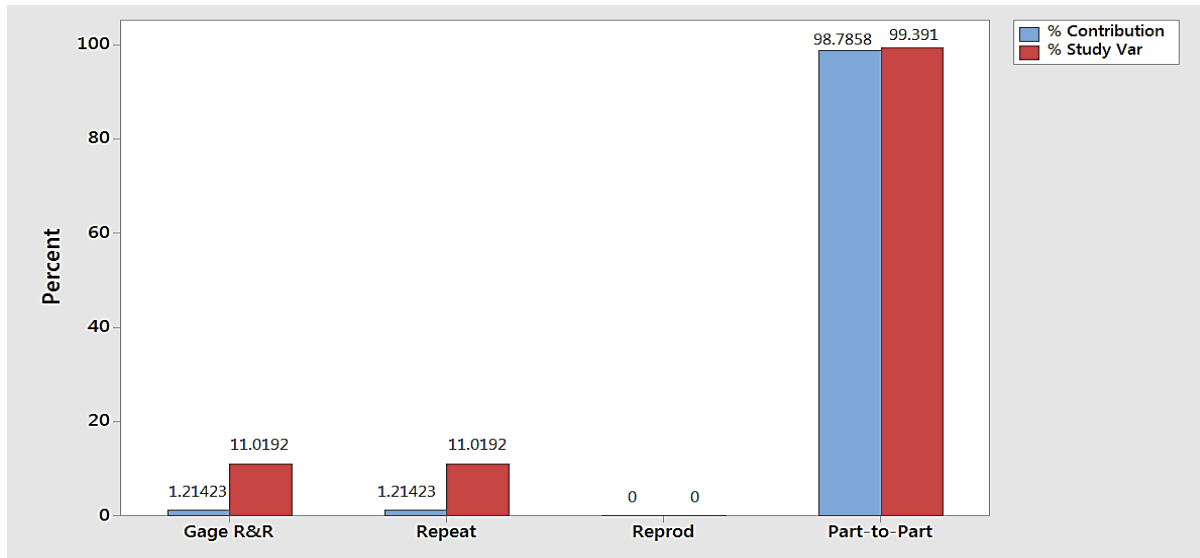


FIGURE 5: Components of variation graph (from Minitab) for Plate 5 position 12c measurements

TABLE 4 Two-Way ANOVA Table with Interaction

Source	DF	SS	MS	F	P
Part	6	0.0005974	0.0000996	896.143	0.000
Operator	2	0.0000002	0.0000001	1.000	0.397
Part * Operator	12	0.0000013	0.0000001	0.778	0.699
Repeatability	42	0.0000060	0.0000001		
Total	62	0.0006050			

α to remove interaction term = 0.05

TABLE 5 Two-Way ANOVA Table without Interaction

Source	DF	SS	MS	F	P
Part	6	0.0005974	0.0000996	733.208	0.000
Operator	2	0.0000002	0.0000001	0.818	0.447
Repeatability	54	0.0000073	0.0000001		
Total	62	0.0006050			

TABLE 6 Gage R&R

Source	VarComp	%Contribution (of VarComp)	StdDev (SD)	Study Var (6 × SD)	%Study Var(%SV)
Total Gage R&R	0.0000001	1.21	0.0003685	0.0022111	11.02
Repeatability	0.0000001	1.21	0.0003685	0.0022111	11.02
Reproducibility	0.0000000	0.00	0.0000000	0.0000000	0.00
Operator	0.0000000	0.00	0.0000000	0.0000000	0.00
Part-To-Part	0.0000110	98.79	0.0033239	0.0199435	99.39
Total Variation	0.0000112	100.00	0.0033443	0.0200657	100.00

Number of Distinct Categories = 12

The gage R&R study was applied to the true position, cylindricity, top plane, bottom plane and depth measurements. The results are shown in Table 8.

TABLE 8 Gage R&R Statistics for true position, cylindricity, top plane, bottom plane and depth measurement.

Source	%Study Var(%SV) Cylindricity	%Study Var(%SV) Top Plane	%Study Var(%SV) Bottom Plane	%Study Var(%SV) Depth	%Study Var(%SV) True Position
Total Gage R&R	17.95	6.20	1.80	0.52	2.73
Repeatability	17.95	6.07	1.76	0.51	2.67
Reproducibility	0.00	1.28	0.35	0.10	0.60
Operator	0.00	1.28	0.35	0.10	0.60
Part-To-Part	98.38	99.81	99.98	100.00	99.66
Total Variation	100.00	100.00	100.00	100.00	100.00

Overall, the total gage R&R for all the features being measured are acceptable as they are all less than 30%. The worst being cylindricity at 17.95% and the best being depth at 0.52%.

CONCLUSION

A set of tests were undertaken using the CMM to assess the repeatability and reproducibility of the measurement process. The CMM was set up to take twenty four repetitive measurements and repeated this cycle using multiple Top-hats. The results shown in this paper shows that the CMM is capable of repeatedly measuring the features to the accuracy needed to assess the process which manufactured the Top-hats.

FUTURE WORK

The CMM can be utilised to assess the geometry changes of parts that have just been manufactured, heat treated and removed from the build plate. The geometry can also be assessed across the build plate and compared to other similar machines. The information can also be compared with different builds to look for patterns and to assess the integrity of the manufacturing process.

REFERENCES

1. Rebaioli L, Fassi I. A review on benchmark artifacts for evaluating the geometrical performance of additive manufacturing processes. *Int J Adv Manuf Technol. The International Journal of Advanced Manufacturing Technology*; 2017;93(5–8):2571–98.
2. British Standards Institution. BS 7172:1989. Guide to assessment of position, size and departure from nominal form of geometric features. London: British Standards Institution; 1989.
3. Flack D. CMM Measurement Strategies. *Good Pract Guid.* 2001;(41).
4. British Standards Institution. BS ISO 22514-7:2012. Statistical methods in process management. Capability and performance. Capability of measurement processes. London: British Standards Institution; 2012
5. British Standards Institution. BS EN ISO 10360-2:2009. Geometrical product specifications (GPS). Acceptance and reverification tests for coordinate measuring machines (CMM). CMMs used for measuring linear dimensions. London: British Standards Institution; 2009
6. Dietrich E. Fähigkeitsnachweis von Messsystemen. Leitfaden Ref Man [Internet]. 2002;(September 2002):109. Available from: http://www.q-das.com/fileadmin/files2/qdasguideline_msa/Leitfaden_v21_me.pdf

GEOMETRICAL DESIGN AND ASSESSMENT OF AN INDUSTRIALLY RELEVANT BENCHMARK PART FOR SELECTIVE LASER MELTING

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INTRODUCTION

Compared to conventional machining, Additive Manufacturing (AM) still faces challenges with respect to the achievable geometrical and dimensional accuracy, surface topology and the resolution of small features [1]. In Selective Laser Melting (SLM), a powder-bed production process where the primary energy source consists of a laser, some areas of powder are selectively melted, layer by layer, to create a full three-dimensional part (FIGURE 1).

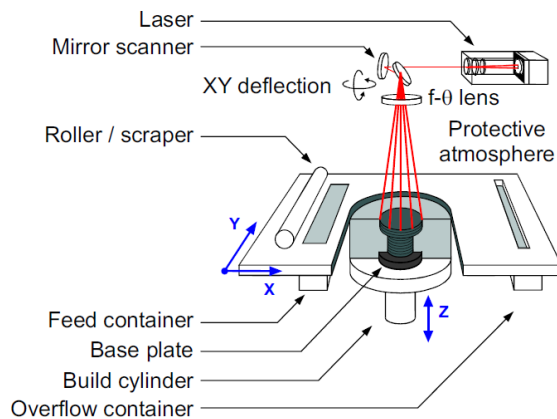


FIGURE 1. Schematic of SLM setup

The quality of parts produced in this manner is a widely investigated topic. For example, roughness of SLM parts often varies from material to material, but is across the board higher than in the case of conventionally machined surfaces: often Ra values of 20 μm are recorded [4] in contrast with normal milled surfaces having an Ra of factor 10 lower [5]. Geometrical errors on the printed parts are due to the processing method, among these for example are the following:

- Shrinkage
- Laser contour offset

- F-theta lens imperfections in the flat field correction
- Feature resolution limitation due to limited particle size
- Etc.

These errors need to be assessed in order to correctly calibrate the process and improve part quality. For all the aforementioned aspects, substantial improvements are required in order to increase the range of industrial applications of SLM-AM.

PROPOSED METHOD

Benchmark parts are a well-known approach to qualify the process capabilities. Several benchmark parts specific to Additive Manufacturing have already been proposed, some of which are described in literature [2], but most of which have only really been used within the companies or research institutes that developed them. This is mainly because different research groups are focused on different aspects of the produced components, while the benchmark part they use is designed in view of the specific measuring instruments they have available to measure that part.

Consequently, the available Additive Manufacturing benchmark parts don't comprise all the features that the industrial consortium involved in the current project considered necessary. Here, the NIST benchmark part for AM (2014) [6] was adapted to include features from use cases of the industrial consortium (FIGURE 2).

In the scope of this project, the benchmark parts were built by SLM of Stainless Steel 316L using four SLM machines from different manufacturers, each using their own optimal methods, strategies and parameters to deliver

what is, according to them, their state-of-practice best part.

A subsequent comparison was made between the different build jobs to follow up on changes in the process and to determine which strategies work better and why.

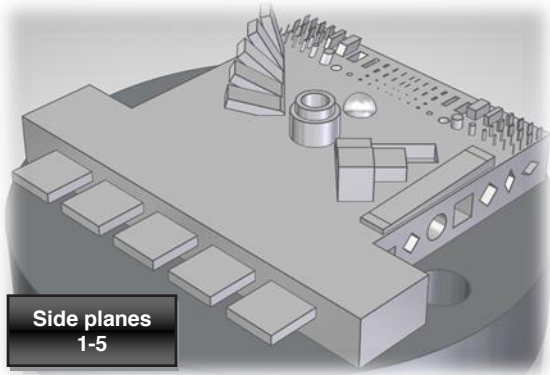


FIGURE 2. New benchmark part, on a cylindrical baseplate of 10 cm diameter

Measurements

The geometrical features were measured using a tactile probing Coordinate Measurement Machine, tactile surface profilometer for roughness measurements, optical microscopy and X-Ray Computed Tomography.

These measurement results were then used to quantify roughness, dimensional and geometric deviations of small features like small pins and holes with diameters ranging from 50 μm to 2 mm in dimensions, and of other larger features with commonly known issues such as support structures and round objects. Also both up- and down-facing sloping surfaces and surfaces prone to warping were investigated as these are known to induce dimensional inaccuracy in powder-bed based AM parts (FIGURE 3).

The results of this study allow to assess the current state-of-practice in industry, and to formulate advices regarding the optimization of part design for AM and regarding possible process alterations. It allows to track changes made in the process parameters and to compare different production iterations. Tensile bars are also integrated in the benchmark part so that the mechanical material behavior can be studied and linked with the outcome of the dimensional analysis, within a single build job to avoid discrepancies.

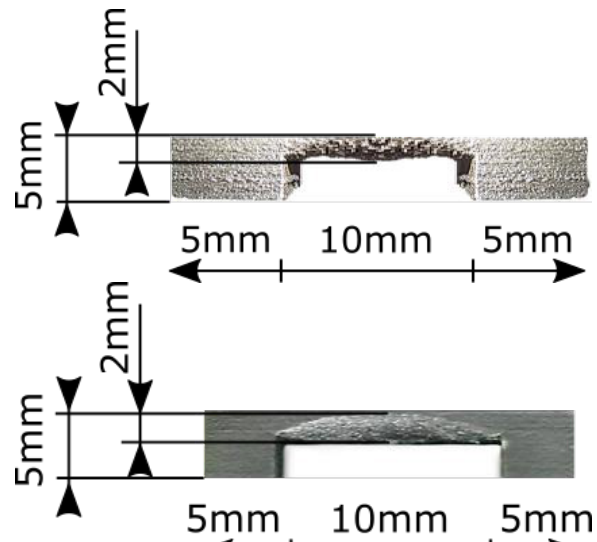


FIGURE 3. Overhangs with dross formation (top) and improvements due to control strategy (bottom) [10]

Overall aim

The proposed Benchmark Part in this study is not meant to be a “global standard”, but rather an example of why such a standard is very difficult to define, as different parties view different aspects and use cases as either high priority, or as not important at all. There has recently been a lot of development on these ideas, and for example, NIST recently held a competition to gather ideas for this specific topic.

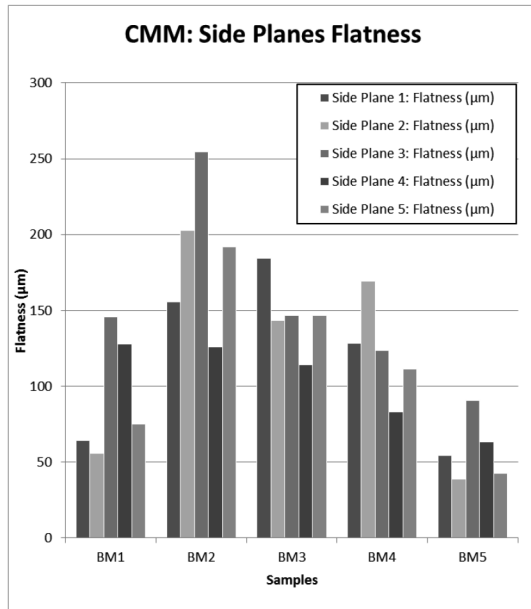
The overall goal of this study within the aforementioned project is to improve the feature resolution, surface roughness and geometrical accuracy, by using feedback from the measurements of different samples part of the benchmark to adapt the design, parameter choice and production strategies used for the next iterations. It also aims at improving the speed of the production process while maintaining a consistent and reliable quality of produced parts. This will be accomplished using new types of hardware to reduce laser scanning time, and newly developed strategies for processing a build job, such as intermittent remelting of layers at a far higher scanning speeds.

MEASUREMENT RESULTS

In the following section the results will be discussed in detail. Five benchmark parts (BM1 to BM5) were measured.

Dimensional measurements using CMM

A NIKON LK Altera CMM was used to perform a pre-determined automated measurement protocol on all of the samples. This was done to avoid any user influence on the results. The most relevant results were gathered below.



GRAPH 1. Flatness of Side Planes

In GRAPH 1 we can see the flatness measurements for the side planes on the part. These are meant to test different support structures, assessing their effects on the topology of overhangs. This is telling of how the support structure used in the part can influence a thin plane that's placed above it. The supports in BM1 and BM5 were more sturdy than the other ones (see FIGURE 4).

TABLE 1. Inclined Plane Measurements

Measured Properties	Nominal	BM1	BM2	BM3	BM4	BM5
Inclined Plane 1: Angle (°)	15	16,92	15,24	15,62	16,78	22,81
Inclined Plane 2: Angle (°)	30	30,28	30,15	30,66	30,35	34,21
Inclined Plane 3: Angle (°)	45	45,30	44,95	45,39	45,47	44,72
Inclined Plane 4: Angle (°)	60	60,12	59,99	59,85	59,97	60,11
Inclined Plane 5: Angle (°)	75	74,55	74,87	74,27	75,52	74,67
Inclined Plane 1: Flatness (μm)	(none)	98,83	42,3	68,59	326,9	458,9
Inclined Plane 2: Flatness (μm)	(none)	70,15	81,01	26,34	59,63	467,2
Inclined Plane 3: Flatness (μm)	(none)	75,97	70,4	17,48	85,19	95,62
Inclined Plane 4: Flatness (μm)	(none)	24,54	40,2	61,7	71,01	30,62
Inclined Plane 5: Flatness (μm)	(none)	32,39	22,56	31,43	68,82	30,11

In TABLE 1 We can see the measurement results for the inclined planes. The planes at 15° and at 30° were built with support structures. Here we can see that in terms of the flatness, even though we used support structures, the flatness of these two is the worst overall. As for the accuracy of building angle, there seems to be an offset for BM5 for these first two, but not for the others. This correlates to the flatness measurements: these planes were the ones that curled up, which both ruins the flatness and makes the next layer during the build more prone to errors. This is because the slight elevation will damage the coater wiper in this region and which therefore cause more roughness.

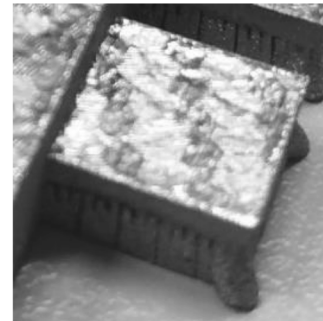
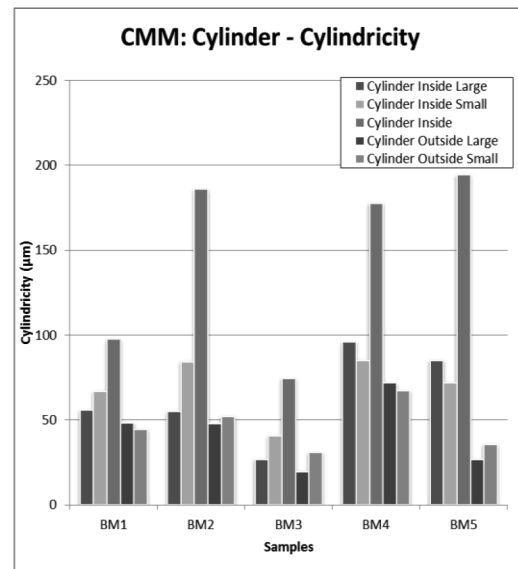


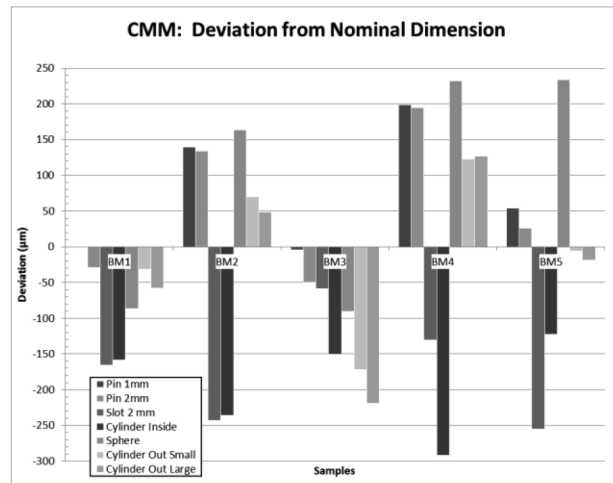
FIGURE 4. Supports under BM5 side planes



GRAPH 2. Cylinder-Cylindricity

GRAPH 2 shows the measured cylindricities of the cylindrical center boss. The "Cylinder Inside" denotes the whole inside cylinder, which has a constant radius, whereas the "large" and "small" sections are measured at those regions where

the outer cylinder is large or small in diameter (see FIGURE 2). It is therefore logical that the former value is higher than the others. What we can see from this graph is that even in the center of the part, there can be quite some deviation from normal tolerances. General medium dimensional tolerance for cylindricity is 100 μm for this diameter (5 mm) [7].



GRAPH 3. Deviation from Nominal Dimension

In GRAPH 3 we can see the dimensional deviations of several features on these parts. Here we can make a conclusion as to scaling errors that might persist. E.g., BM1 has a negative error on all dimensions listed. This might require a scale-up to correct. The same holds true for BM3. The other parts show changing dimensional error signs, which might be due to a wrong laser beam offset value. Also something to bear in mind is the fact that small features have dross-like sintered powder attached to the sides, influencing the dimensions, usually resulting in these being too large.

Conclusion

Using a CMM we can clearly define several feature deviations that are important for optimal part production. Mainly scaling errors and larger deviations due to warping, curling and other deformations can be measured.

Roughness Measurements

Using a Taylor-Hobson Talysurf profilometer, the linear roughness parameters were assessed.

Roughness (μm)	BM1	BM2	BM3	BM4	BM5
Top Surface Roughness Ra	20,3	24,1	17,1	16,4	8,9
Top Surface Roughness Rt	244,8	295,6	100,5	234,6	81,9

TABLE 2. Roughness Ra and Rt

TABLE 2 shows that BM5 has by far the lowest roughness. This part was produced using a significantly different scanning strategy, using polygonal islands that are scanned in stripes. This greatly reduced the roughness. This strategy therefore seems very promising and will be researched further.

One remark is that the currently accepted and widely used methods for analyzing product surfaces is very much tailored to conventional machining, where high roughness on short and non-linear data lengths are rare. To ensure correct measurement of the Ra value here, ISO standards were followed on a 40 mm data length for Ra over 10 μm [9].

Optical Microscopy Measurements

An optical microscope (Keyence VHX 6000) was used to measure the different fine features were possible. Due to the highly reflective material for an optical measurement method, this was mainly restricted to pins instead of slots. In the following table, 'R' denote rectangular pin and 'C' denotes circular pin.

Fine Features (μm)	Nominal	BM1	BM2	BM3	BM4	BM5
Edge Effect		256	263	248	251	254
Slope Steps	750	753	762	751	1140	719
R500	500	567	671	554	463	528
R250	250	336	433	306	255	318
R100	100	Not printed	Not printed	176	228	172
R50	50	Not printed	Not printed	Not printed	263	175
C500 (radius)	250	274	355	271	226	266
C250 (radius)	125	171	153	154	Not printed	159
C100 (radius)	50	Not printed	Not printed	143	Not printed	107
C50 (radius)	25	Not printed	Not printed	Not printed	Not printed	Not printed

TABLE 3. Fine Feature Dimensions

TABLE 3 depicts the different measurements and the nominal value for each feature. Here we can see that there is clearly a difficulty printing the smaller features. Below 200 μm , all benchmarks start showing this. As the dimensions of the features go down, the deviations from the nominal become more and more positive. This is of course logical, as there will be too much powder attached to the sides of those features, rather than too little. As we are approaching the particle size of the used powder (between 25 and 45 μm), we see that they definitely pose a limit. The smallest achievable

feature in this test was a $107\text{ }\mu\text{m}$ radius ($214\text{ }\mu\text{m}$ diameter) circular pin. It is one of the main goals of the project to reduce this by using a pulsed laser to erode excess material from the sides of the features in-process.

Another aspect we can see from this result is the so-called “elevated edge”-effect (FIGURE 5) This is the effect where the borders of the top surface have a clear sharp upward bevel. This is likely caused by denudation processes, in which the large amount of free powder at the edges gets incorporated in the melt pool, hence locally increasing the volume of molten material.



FIGURE 5. Elevated Edge Effect

The “slope steps” pertain to the slope feature on top of the benchmark part. This feature has a height of 1 mm and a specific known length. This can be used as a way to see what happens in every consecutive layer. The value shown is simply the distance in X-direction between the layer steps (the step “depth”). Using the dimensions of this slope, we can see that part BM4 was built using a layer thickness of $40\text{ }\mu\text{m}$ as opposed to all others being made with $30\text{ }\mu\text{m}$ layers. This can have an influence on the surface finish, yet in this case we did not see a significant difference when we look at the roughness results (TABLE 2).

Conclusion

The optical microscopy method can show us in detail how the smaller features are built, as long as they are not slots. These are notoriously difficult to measure using optical microscopy, certainly at the dimensions considered here.

CONCLUSION

Using the information gained in this measurement protocol, we can more easily identify common errors and faults in the process and in the interactions between the different parameters that are used. Scaling and calibration errors can be identified, influencing factors for roughness and other dimensional and geometrical deviations can be found, and strategies can be chosen to push the boundary of what is possible to make using SLM-AM. Benchmark parts should however be designed with a specific set of features in mind. For research it is therefore common practice to design own custom benchmarks. A universal standardized benchmark would be useful to compare and relate different machines in a production environment.

FUTURE WORK

From this we can conclude that the optical microscopy can definitely give a great insight in the dimensional aspects of the finer features, yet it lacks with regards to the measurement of small slots. Therefore we will use X Ray Computed Tomography measurements in the future to assess such features. This will also offer more insight in the porosity aspects while benchmarking, which may be critical in such small parts as the energy input is very localized, and might induce a lot of keyhole porosity [8].

The benchmark parts have to be continually produced as the process is improved. This will allow for easy reference measurements and feedback in the process improvement cycle.

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REFERENCES

- [1] Strano, G., Hao, L., Everson, R., Evans, K. Surface roughness analysis, modelling and prediction in selective laser sintering. Journal of Materials Processing Technology. 2012.
- [2] Kruth, J.-P., Vandenbrouke, B., Van Vaerenbergh, J., Mercelis, P. Benchmarking of different SLS/SLM

- processes as Rapid Manufacturing techniques. Int. Conf. Polymers & Moulds Innovations (PMI). 2005.
- [3] Yase, E., Deckers, J., Craeghs, T., Badrossamay, M., Kruth, J.-P. Investigation on Occurrence of Elevated Edges in Selective Laser Melting. 20th Solid freeform fabrication symposium. 2009.
 - [4] Fox, J., Moylan, P., Lane, B. Effect of process parameters on the surface roughness of overhanging structures in laser powder bed fusion additive manufacturing. 3rd CIRP Conference on Surface Integrity (CIRP CSI). 2016.
 - [5] Mathew, A., Kuttolamadom, S. H., Laine Mears, M. Effect of Machining Feed on Surface Roughness in Cutting 6061 Aluminum. Clemson University - International Center for Automotive Research. 2010.
 - [6] Moylan, S., Slotwinski, J., Cooke, A., Jurrens, K., Donmez, M. A. An Additive Manufacturing Test Artifact. Journal of Research of the National Institute of Standards and Technology. 2014.
 - [7] Dax, W., Gundelfinger, K., Häffner, W., Itschner, H., Kotsch, G. Basistolerantie voor vorm en plaats voor onderdelen die vervaardigd worden door verspanen en omvormen. Tabellenboek voor metaaltechniek. 1996.
 - [8] Chou, K., Shrestha, S. Porosity analysis in metal additive manufacturing by micro-ct. Micro-CT user meeting. 2018.
 - [9] ISO 4287: 1996.
 - [10] Buls, S. A Smart Machine for Selective Laser Melting: A Controlled & Synchronized System Approach. 2018.

Concurrent Optimization of Geometry and Strength of FDM Printed Parts

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ABSTRACT

Investigations into the achievable geometrical and mechanical properties of parts printed with the fused deposition modelling (FDM) technique has been done by several researchers. This paper presents research on process parameters affecting both the geometrical and mechanical properties of fused deposition modelling printed parts. Based on these results, a process optimization was performed using Taguchi's statistical analysis method to evaluate the optimum print conditions for both the geometrical and mechanical properties.

Keywords: fused deposition modelling, geometrical properties, mechanical properties

INTRODUCTION

Additive Manufacturing (AM) processes are processes that build physical objects layer by layer. They are commonly used by engineers and designers in the manufacture of prototypes for visual aids and presentation models. These processes are highly preferred in the manufacture of components with complex geometries and in small volume manufacturing environment as they do not require significant tooling. This has an advantage over traditional manufacturing processes, in terms of savings in material used, component cost and shorter manufacturing cycle time. Some of these processes include selective laser sintering (SLS), 3D printing (3DP) and fused deposition modelling (FDM).

With recent developments in rapid prototyping technologies, these processes are now being used in the manufacture of end user products in

many small volume manufacturing environments. However, for these rapid prototyping processes, and for the FDM process in particular, it has been shown in earlier researches that the quality, in terms of the geometrical and mechanical properties [1–5], of the printed components highly depends on the proper selection of the printing parameters used.

This article aims to study the effects of variation in the process parameters settings on the geometrical and mechanical properties of parts, manufactured using a consumer grade desktop FDM 3D printer.

This was performed by first consolidating a list of process parameters available in a consumer grade FDM 3D printer and by using Taguchi's design of experiment (DOE) method. An experimental plan was developed based on the number of process parameters considered and their control levels. The FDM 3D printer used in the experiment was the Makerbot Replicator 2X and parts were printed with ABS (Acrylonitrile Butadiene Styrene) filament.

The measurements and data collected for both the dimensional accuracy and tensile strength were evaluated and critical parameters affecting each of the properties investigated were identified and the theoretical optimum print conditions were found for each of the properties considered.

METHODOLOGY

For this paper, the influence of thirteen parameters, with three levels of control, on the dimensional accuracy and tensile strength of the

printed parts were considered, as shown in Table 1, and the corresponding control levels as shown in Table 2. Using Taguchi's design of experiment method, with thirteen parameters and three levels of control, a L_{27} orthogonal array was used to develop the experimental plan for this investigation and a total of 27 experimental printing conditions were used.

Table 1. Process parameters considered for this investigation.

Parameter	Description	Units
A	Part size	%
B	Print location	-
C	Extruder temp.	°C
D	Print orientation	°
E	Travel speed	mm/s
F	Extrusion speed	mm/s
G	Buildplate temp.	°C
H	Peeling temp.	°C
J	Layer thickness	mm
K	Infill density	%
L	Number of shells	-
M	Infill pattern	-
N	Infill shell spacing	mm

Table 2. Parameters and the corresponding control levels.

Parameter No.	Control Levels		
	1	2	3
A	80	100	120
B	Left	Center	Right
C	218.5	230.0	241.5
D	45	0	-45
E	120	150	180
F	72	90	108
G	104.5	110.0	115.5
H	38	40	42
J	0.16	0.20	0.24
K	8	10	12
L	1	2	3
M	linear	hex	moroccanstar
N	0.64	0.80	0.96

Geometric Properties

For the study of the geometric properties, this research focused on the dimensional accuracy of the printed parts. The dimensional accuracy refers to the difference between the nominal and

the measured values of the printed part; the accuracy is evaluated by the difference of these two dimensions, the smaller the difference, the more accurate is the print out. A benchmark component was designed [6], as shown in Figure 1, to include simple geometric features, such as circles and squares, which allow for reliable dimensional measurements and evaluation of the dimensional accuracy of the printed benchmark components.

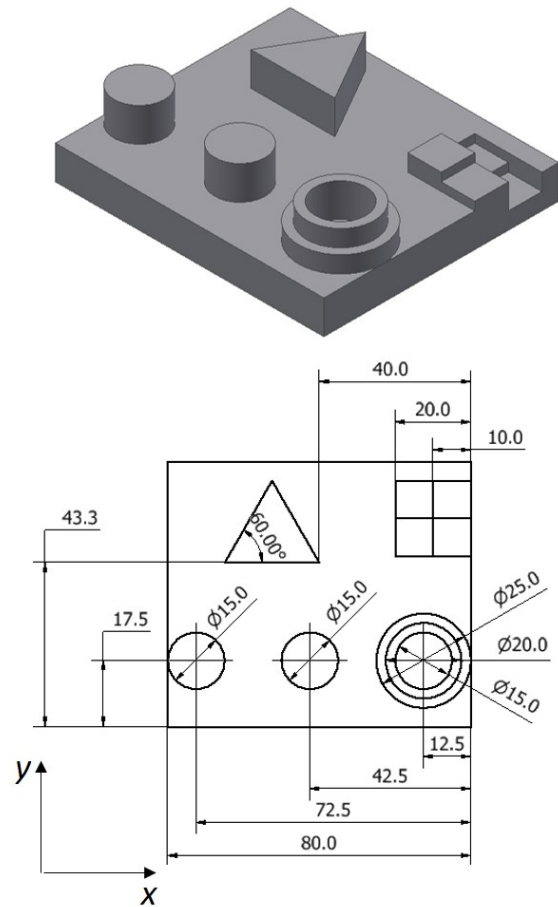


Figure 1. Benchmark component used for dimension accuracy study.

Measurements for length (x), width (y), height (z) and diameter (v) were taken and the deviation was calculated. For geometric property, 27 benchmark components were printed according to the experimental plan.

Mechanical properties

For the mechanical property, the research aimed to investigate the tensile strength of the printed specimens [7] as function of the printing parameters. Tensile specimens were based on

ISO 527 Type 1BA test standard specimens, shown in Figure 2, with the thickness, h , ranging from 2mm (Level 1 control) to 6mm (Level 3 control) to assess the effects of part thickness, h , on its tensile strength.

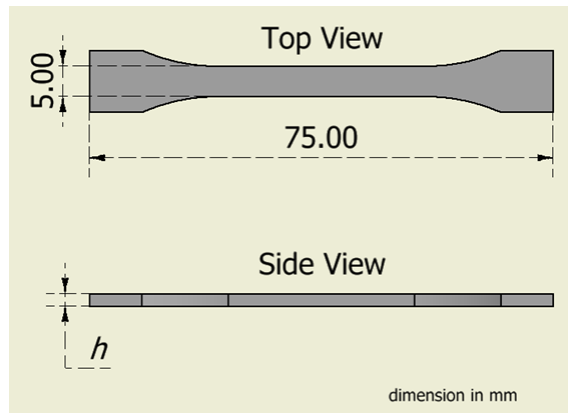


Figure 2. Tensile specimen for mechanical strength evaluation.

For the mechanical properties, three specimens were printed for each printing conditions to ensure consistency and repeatability of the data.

RESULTS & ANALYSIS

All specimens were printed, for geometrical accuracy and mechanical tensile strength, according to the experimental plan and measurement results were collected and analyzed. Using Taguchi's design of experiment method, the response to signal-to-noise ratio (SNR) and means were calculated. The parameters influence on the respective property were ranked according to their importance. For geometrical property, the "smaller-is-better" response characteristics was used whereas for the mechanical property, the "larger-is-better" response characteristics was used.

The response for SNR (geometric properties) is shown in Table 3. From Table 3, it can be seen that the three main parameters affecting the dimensional accuracy of a printed part were: the part size (A), buildplate temperature (G), layer thickness (J).

For the mechanical properties (Table 4), it can be seen that part size (A) is ranked the highest, similar to the response for SNR for geometric property. This is followed by number of shells (L) and print orientation (D).

It can be seen that by increasing the thickness of the specimen, the overall cross-section of the specimen also increased. Therefore, there was a higher amount of material within the cross-sectional area and this improved the overall strength of the specimen. Similarly, a higher number of shells improved the strength in the outer shells and thus increased the strength of the printed part.

For the print orientation, it can be seen that the response for SNR was the highest for the level of control 2, corresponding to a print orientation of zero degree, at this orientation, the deposited filaments of material were aligned with the axial direction of the tensile test. Therefore, increasing the overall strength of the parts as the printed filaments were in tension. This shows that the strength of 3D printed parts is a function of its printing angle. It also shows that 3D printing produces parts that are anisotropic.

During this investigation it was observed that several specimens experienced severe warpage and shrinkage as shown in Figure 3. The warpage was typically located in one of the corners of the part.



Figure 3. Specimen warpage

CONCLUSIONS

This paper investigated the effects of varying print conditions on the dimensional accuracy and tensile strength of parts printed using the FDM process. Thirteen parameters were considered for this investigation and using Taguchi's design of experiment method, an experimental plan was developed and used.

Benchmark components, for dimension, and tensile specimens, for mechanical strength, were printed according to the experimental plan. The experimental data collected was used to investigate the effects of varying print parameters on the geometric and mechanical properties of FDM printed parts.

Table 3. Response table for SNR (Geometric property) [8]

Geometrical Feature	Parameters from Table 1												
	A	B	C	D	E	F	G	H	J	K	L	M	N
Length	2.71	1.82	4.00	1.35	3.11	1.81	3.39	3.02	1.42	3.07	2.17	5.77	2.57
Width	2.52	1.92	0.28	3.16	1.59	2.03	1.09	1.94	1.92	1.86	0.15	1.92	2.91
Diameter	0.85	0.86	0.11	0.37	0.35	0.21	0.41	0.15	0.56	0.25	0.61	0.24	0.34
Height	4.71	2.36	1.93	4.45	0.94	1.50	5.01	0.49	5.01	2.10	2.79	1.91	2.11
Deviation - X	3.31	1.12	2.60	3.32	1.06	1.12	3.51	0.96	2.78	2.04	0.24	0.12	2.53
Deviation - Y	3.86	0.61	4.44	1.10	2.93	2.42	2.95	1.28	2.73	2.47	2.70	3.32	2.87
Sum	17.95	8.69	13.36	13.75	9.98	9.08	16.37	7.84	14.42	11.79	8.66	13.28	13.34
Ranking	1	11	5	4	9	10	2	13	3	8	12	7	6

Units of measurement: db

Table 4. Response table for SNR (Mechanical property) [7]

Control Levels	Parameters from Table 1												
	A	B	C	D	E	F	G	H	J	K	L	M	N
1	27.29	25.37	25.21	25.01	25.11	25.71	25.11	25.36	25.43	25.45	23.63	25.34	25.71
2	24.73	24.86	25.19	25.92	25.52	25.06	25.74	24.80	24.65	24.94	25.44	25.35	24.97
3	23.58	25.36	25.18	24.66	24.96	24.82	24.74	25.43	25.52	25.20	26.53	24.90	24.92
Delta	3.71	0.51	0.03	1.26	0.55	0.88	1.00	0.62	0.87	0.50	2.90	0.44	0.79
Ranking	1	10	13	3	9	5	4	8	6	11	2	12	7

Units of measurement: db

It was found that for dimensional accuracy, the three key parameters are:

1. part size,
2. buildplate temperature and
3. layer thickness.

And for an improved tensile strength, the three more important parameters are:

1. part size,
2. number of shells and
3. print orientation.

From these results, it was shown that part size is a critical parameter for both the geometric and mechanical properties of parts printed via the FDM process.

Based on the results obtained from this investigation, further work can be done to improve the FDM process; a set of print conditions which optimize both geometrical and mechanical properties of the printed parts.

The printing conditions that leads to warpage and shrinkage of the 3D printed part should also be investigated so that these unwanted phenomena can be avoided by the end user.

REFERENCES

- [1] Montero M, Roundy S, Odell D, Material characterization of fused deposition modeling (FDM) ABS by designed experiments, In: Proceedings of Rapid Prototyping & Manufacturing Conference. Society of Manufacturing Engineers; 2001: p. 1–21.
- [2] Nanchaiah T, Raju D, Raju V, An experimental investigation on surface quality and dimensional accuracy of FDM components, International Journal on Emerging Technologies [Internet]. 2010 [cited 2014 Dec 14]; 1(2): 106–11. Available from: <http://researchtrend.net/ijet12/20.pdf>
- [3] Fatimatuzahraa AW, Farahaina B, Yusoff WAY, The effect of employing different raster orientations on the mechanical

properties and microstructure of Fused Deposition Modeling parts, In: 2011 IEEE Symposium on Business, Engineering and Industrial Applications. Langkawi, Malaysia; 2011: p. 22–7.

- [4] Kumar S, Kannan V, Sankaranarayanan G, Parameter Optimization of ABS-M30i Parts Produced by Fused Deposition Modeling for Minimum Surface Roughness, International Journal of Current Engineering and Technology. 2014;(3): 93–7.
- [5] Moza Z, Kiskakis K, Kechagias J, Vaxevanidis NM, Medical applications of 3D printing-A dimensional accuracy investigation of low cost 3D printing, International Conference on Food and Biosystems Engineering. 2015;(MAY).
- [6] Shahrain M, Didier T, Lim GK, Qureshi AJ, Fast Deviation Simulation for 'Fused Deposition Modeling' Process, Procedia CIRP. 2016; 43: 327–32.
- [7] Qureshi AJ, Mahmood S, Wong WLE, Talamona D, Design for scalability and strength optimisation for components created through FDM process, In: Proceedings of the 20th International Conference on Engineering Design (ICED2015). Milan, Italy, 27-30.07.2015; 2015: p. 255–66.
- [8] Mahmood S, Talamona D, Goh KL, Qureshi AJ, Fast deviation simulation for 'Fused Deposition Modelling' process, In: 14th CIRP CAT 2016 - CIRP Conference on Computer Aided Tolerancing. Gothenburg, Sweden: Procedia CIRP; 2016: p. 327–32.

A CLASSIFICATION SCHEME FOR AM CONTROL STRATEGIES: THE AM V-MODEL

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INTRODUCTION

The current lack of consistent additive manufacturing (AM) part quality gives rise to the development of novel process monitoring and control strategies [1]. The identification of these strategies can be facilitated by formulating a classification scheme to position development efforts. This work proposes a classification scheme that was developed in the context of vat photopolymerization [2], but is expected to be applicable to a wide range of AM technologies since many commonalities exist in the multi-level control characteristics.

EXISTING CLASSIFICATION SCHEMES

General control system hierarchies for mechatronic systems [3] and the process industry [4] can be found in literature. Specific classification schemes for AM control strategies can be found in literature as well; most notable are the NIST control organizational structure for metal-based AM [5], the Zero Defects for Additive Manufacturing (ZeDAM) quality control strategy architecture [6] and a hierarchical control method framework for

an Exposure Controlled Projection Lithography (ECPL) process [7]. Inspired by these existing schemes and based on examples from literature, a more elaborate classification scheme for AM control strategies is proposed in this work.

PROPOSED SCHEME: THE AM V-MODEL

The planning and realization of a 3D product through an additive manufacturing process can be viewed of as analogous to the following of a V-model, which is a well-known graphical representation of the systems engineering process [8]. Figure 1 shows such a V-model with the type of control strategy indicated in the middle of the V, where the verification and validation arrows are commonly drawn. The left leg of the V concerns process planning or setpoint generation, where a spatial decomposition is made from product geometry via layers into voxels, the elementary building block of the product. The right leg of the V concerns process execution, where the product is built up, usually layer-by-layer, through the patterned supply and transformation of material.

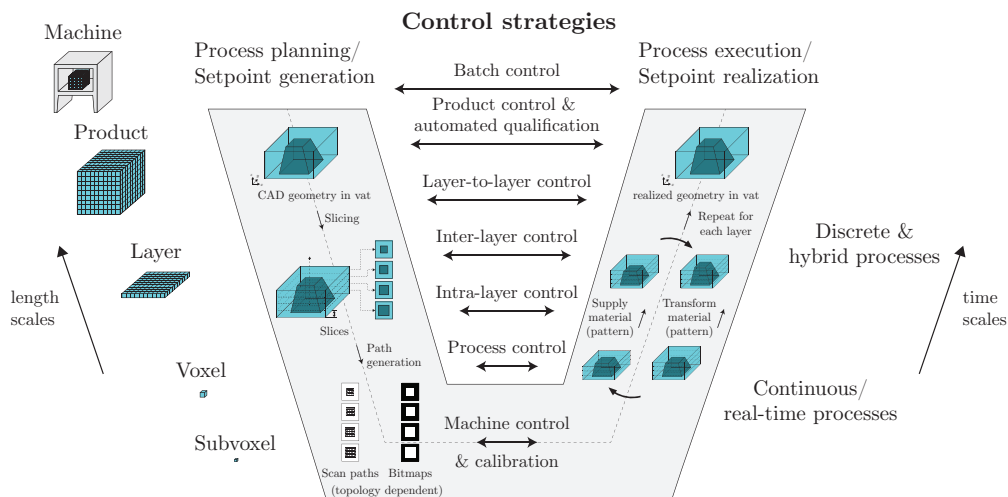


FIGURE 1. The AM V-model hierarchy.

A decomposition of the AM process can be made across both the spatial axis and the time axis as indicated on the left and right sides of the V respectively. Process planning — the complete left leg of the V — can be considered a control strategy in itself. Control strategies for process execution — the complete right leg — can be conceived at each level in the V. Seven such categories can be identified from low- to high-level control: machine control & calibration, process control, intra-layer control, layer control, layer-to-layer control, product control & qualification, and batch control.

CONTROL STRATEGY CATEGORIES

Process planning

Process planning in AM primarily consists of placing and orienting the part in the build volume, generating supports, slicing, and path planning [9]. From a control system's perspective, process planning is the offline procedure of generating the reference trajectories or setpoints, or in other words determining the build process parameters and inputs. It can be considered a form of open-loop control, including the generation of feedforward inputs, and is complementary to closed-loop feedback control.

Traditionally the determination of optimal process parameters would proceed via expensive time-consuming trial and error iterations on the actual machine, whereas currently there is a shift towards input parameter optimization through build simulation using high-fidelity physics-based process models [5]. Structural topology design optimization [10] with manufacturability constraints or design for AM can also be noted here. Regardless of the manner obtained, the final result of the process planning procedure is a set of machine instructions stored in a build plan. Figure 2 shows the generation of machine instructions from product geometry during process planning.

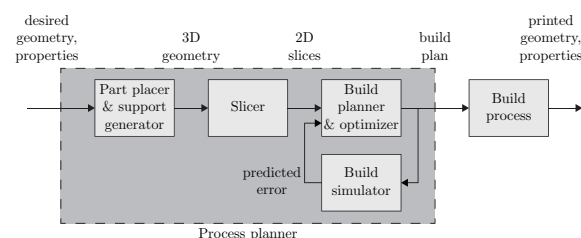


FIGURE 2. Process planning scheme.

Examples of process planning for vat photopolymerization include laser scan trajectory gener-

ation, bitmap greyscaling for improved xy - or z -resolution, and inverse geometry compensation for deformations arising during the build.

Machine control & calibration

Low-level *machine control* systems have always been an essential part of any AM machine, since these systems provide basic functionality such as motion control or process parameter control. Machine control systems focus on individual machine functions, which are independent of the process details such as product geometry and material. The goal of these systems is to provide desired process parameter (input) trajectories and to pursue practically constant boundary conditions. Hereby they only *indirectly* influence the actual manufacturing process [11], which consists of a complex coupled material property and geometry transformation.

An example of machine control is motion control for patterning the *supply* of material, patterning the *transformation* of material as shown in Figure 3, or elevating the build platform. Positioning errors, owing to the precision and accuracy of the motion stages and scanners, will lead to geometric variations in the part. However, disturbances to these process-independent machine state variables are generally considered small compared to other process variables that do directly affect the quality of the output [12]. Another example is build chamber environment control, which includes temperature, oxygen concentration and pressure control at several locations throughout the machine. Monitoring and control of these machine state variables is typically performed by logging at low sampling frequencies and by warning indicators or independent SISO control loops [13].

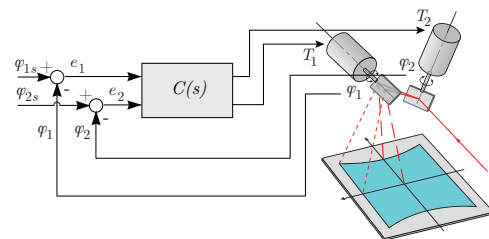


FIGURE 3. Machine control example.

Calibration

A different aspect that can also be gathered under machine control is *calibration* and subsequent adjustment or drift correction. Calibration is the act of comparing measurement values of unknown accuracy to a measurement standard of known

accuracy. In AM this means that both the material supply and transformation systems can be calibrated with respect to a calibration standard. For instance, the position of the laser scanning system can be calibrated to a reference plate placed over the build platform [14] or to fiducial markers additionally printed in each layer.

Process control

Contrary to the indirect machine control techniques, *process control* techniques deal directly with the actual manufacturing process, i.e., the production of a desired object through a material transformation process [11]. In AM, this material transformation process is the geometry transformation from feedstock to strands or layers in the recoating process and the material property transformation from, e.g., the liquid to the solid phase in the vat photopolymerization process.

The main idea behind process control strategies is that voxel-level control of material properties [15] can be obtained by real-time, in-situ continuous control [5] of the *material transformation process*. For metal-based processes, examples of process controllers exist in which the temperature or area of the melt pool is controlled [16, 17], see Figure 4. For vat photopolymerization this would imply controlling the polymerization reaction [2].

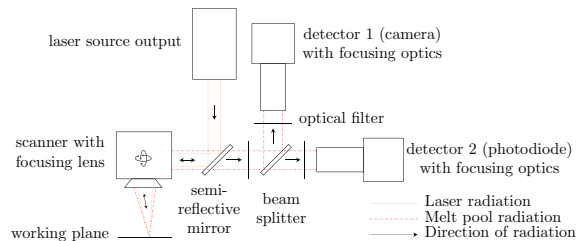


FIGURE 4. Process control example [16].

The *geometry transformation process* from feedstock to a layer, i.e., the recoating process, can also be controlled. However, it is arguable whether this is *machine control* or *process control*, since in some AM technologies such as selective laser sintering (SLS) and vat photopolymerization the *requirement* for the quality deposition [13] of a flat layer is independent of the desired part geometry, even though the recoating process dynamics can be product-dependent. In other words, the material deposition is not patterned in SLS whereas it is patterned in, e.g., Fused Deposition Modeling (FDM). In any case, the feed rate of feedstock material can be controlled to ensure a well-defined amount of mate-

rial at the correct location.

Intra-layer control

Intra-layer control refers to control strategies that take place on the time scale of the processing of a single layer. The idea is to use feedback from the foregoing to improve the process settings for the remainder of the layer. Examples of hypothetical inter-layer control schemes include measuring in the slipstream of the recoater and the scan track behind the laser respectively. These types of control strategies may run at lower control bandwidths than process control strategies and due to their non-colocated nature may lend themselves well to observer-based control schemes that infer the state of the process dynamics at e.g. the laser location from non-colocated measurements. An example of an existing intra-layer control scheme is intra-layer build plan modification of the ordering and timing of hatches [18], see Figure 5.

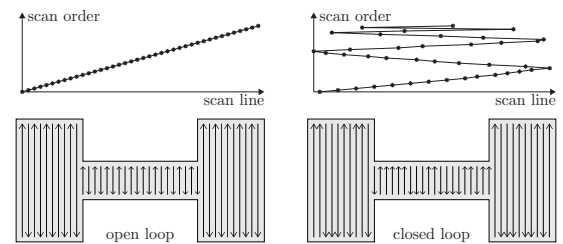


FIGURE 5. Intra-layer control example [18].

Inter-layer control

The goal of *inter-layer control* schemes is to guarantee - by means of feedback control - the quality of each layer after the layer formation step has been completed. These types of schemes do not operate at the frequencies or time scales of the low-level *continuous* or real-time processes such as machine and process control, but can be rather considered *discrete* or hybrid events. Hence, these schemes are of a supervisory control nature and can be designated as in-situ fault detection and handling controllers [5] that trigger discrete events by interrupting normal control routines and performing a corrective action if necessary.

Examples of inter-layer control schemes include corrective resweeping in vat photopolymerization [19] depicted in Figure 6 or respreading in powder-based systems [17]. The machine state variables such as the chamber environment controlled by machine controllers can also be monitored and controlled by a higher supervisory control scheme that interrupts the process if these

variables assume unacceptable values [5].

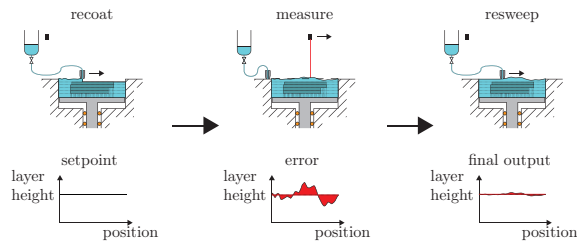


FIGURE 6. Inter-layer control example.

Layer-to-layer control

Layer-to-layer control schemes aim to use information from the current layer N and preceding layers to find better settings for the next layer $N + 1$ as depicted in Figure 7. Specifically, these schemes can leverage that subsequent layers are highly similar, i.e., changes from one layer to another are typically gradual. Moreover, if discontinuous changes from layer to layer occur, *a priori* knowledge hereof could be exploited.

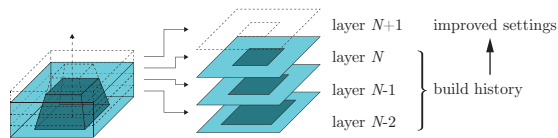


FIGURE 7. Layer-to-layer control.

The formation of a layer can be considered a discrete process where the process inputs - typically depending on the slice cross-section - can be modified *ex situ*, i.e., in between the formation of each layer. Hence layer-to-layer control can be considered similar to run-to-run control, batch-to-batch control or cycle-to-cycle control [7]. Repetitive and iterative learning control strategies may be applicable since the tasks are repetitive and disturbances are position dependent.

Example layer-to-layer control schemes for ink-jet 3D printing include a model-based feedback control law [20] and an iterative learning control law [21] that use a layer height profile measurement from the last layer to determine the droplet deposition pattern for the following layers. Another example is a layer-to-layer height and temperature controller for laser metal deposition [22].

Product control & automated qualification

The next level of control after layer-to-layer control is *product control*, which is concerned with the control of macroscopic product specifications

or properties. The goal of these control strategies is to get the global product properties right and they act on a time scale similar to layer-to-layer controllers where it is still possible to adjust the process before the product is finished. The ultimate controller on the product level would be capable of *automated part qualification* [5] through process monitoring and analysis of product qualities such as dimensional accuracy and material properties.

An apparent example of product control is geometric feedback control, which closes the loop on the overall part geometry level [23]. Another example is closed-loop control of the effective stiffness of a cantilever beam [24]. Future advanced product control schemes would benefit from the tight integration of feedback control with the same multi-physics/finite element simulations and topology optimizations that were used to initially create the build plan [25]. Real-time corrections could be made to machine instructions to meet product specifications [26, 25] as depicted in Figure 8. Note that Figure 8 is the same as Figure 2, but with an additional feedback signal from the build process outputs that represents the digital twin [26] to the build simulator and hence (indirectly) to the build planner & optimizer.

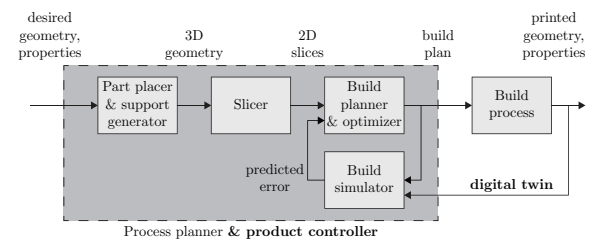


FIGURE 8. Product control scheme.

Batch control

Batch control schemes refer to individual-product-exceeding strategies that apply to the complete build job or batch. It is fairly commonplace in industry to print test specimens such as standardized dog bones oriented in different directions alongside each build to ensure proper material properties of that batch. The printing of additional structures to calibrate the printing process during the build rather than for post-build verification can also be mentioned here.

Batch control typically takes place through *offline* and *ex situ* measurements of printed objects. Non-destructive testing (NDT) and evaluation (NDE) methods are a critical part of quality con-

trol and inspection for AM [27]. A straightforward example is dimensional verification through optical or X-ray computed tomography [27]. Feedback loops can be conceived that modify the process inputs between build batches based on pre- and post-process data obtained through aforementioned NDT metrology. One can also envision a (machine) *learning* system that uses long-term learning from errors occurring during the build process to prevent future occurrence [6]. Manufacturability feedback loops [28] fall under the same category, since feeding back information of process (in-)capabilities to the design process can increase the number of successful builds. The digital thread for AM [26] may play a crucial enabling role in this.

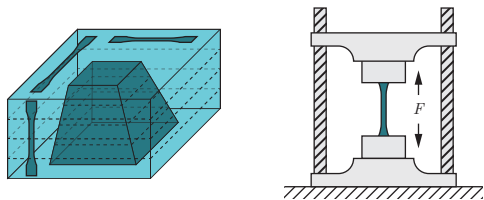


FIGURE 9. Batch control by testing specimens.

COMBINING MULTIPLE CONTROL LEVELS

The foregoing sections describe classes of separate control schemes that can be placed in the respective levels of the control V-model. However, it is thinkable that future AM machines incorporate a multi-level control architecture that combines control strategies from one or more of these levels. Such a hierarchy could be borrowed from the machining industry [29], where machine, process and product controllers are already combined, see Figure 10.

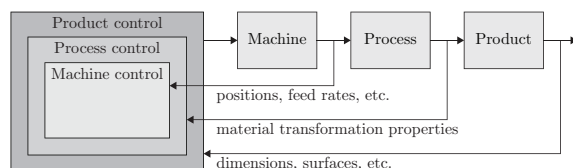


FIGURE 10. Multi-level control hierarchy.

One way to combine multiple controllers, would be to cascade them in series [6]. The main idea behind cascade control is that disturbances can be rejected by a secondary loop before the primary controlled variable deviates from the set-point [4]. In the case of AM, if overall product quality is the controlled variable, it seems sensible to use cascade control to reject disturbances on the voxel or layer scale.

CONCLUSION

This paper presented a classification scheme for AM control strategies, which should serve as a tool to identify potential control strategies. Although example control strategies exist in literature for each level in the AM V-model, closed-loop process and product control is yet to become commonplace in industry.

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REFERENCES

- [1] Huang Y, Leu MC, Mazumder J, Donmez A. Additive manufacturing: Current state, future potential, gaps and needs, and recommendations. *Journal of Manufacturing Science and Engineering*. 2015;137(1):014001.
- [2] Hafkamp T, van Baars G, de Jager B, Etman P. A feasibility study on process monitoring and control in vat photopolymerization of ceramics. *Mechatronics*. 2018;10.1016/j.mechatronics.2018.02.006.
- [3] Isermann R. *Mechatronic systems: fundamentals*. London: Springer; 2005.
- [4] Seborg DE, Edgar TF, Mellichamp DA, Doyle FJ. *Process dynamics and control*. 3rd ed. Hoboken, N.J: John Wiley & Sons, Inc; 2011.
- [5] Vlasea ML, Lane B, Lopez F, Mekhontsev S, Donmez A. Development of powder bed fusion additive manufacturing test bed for enhanced real-time process control. In: *Proceedings Solid Freeform Fabrication Symposium*; 2015. p. 527–539.
- [6] Faes M, Abbeloos W, Vogeler F, Valkenaers H, Coppens K, Ferraris E, et al. Process Monitoring of Extrusion Based 3D Printing via Laser Scanning. In: *PMI 2014 Conference Proceedings*. vol. 6; 2014. p. 363–367.
- [7] Zhao X. *Process Measurement and Control for Exposure Controlled Projection Lithography* [PhD Thesis]. Georgia Institute of Technology; 2017.
- [8] Kossiakoff A, editor. *Systems engineering: principles and practice*. 2nd ed. Hoboken, N.J: Wiley-Interscience; 2011.

- [9] Kulkarni P, Marsan A, Dutta D. A review of process planning techniques in layered manufacturing. *Rapid Prototyping Journal*. 2000 Mar;6(1):18–35.
- [10] Liu J, Gaynor AT, Chen S, Kang Z, Suresh K, Takezawa A, et al. Current and future trends in topology optimization for additive manufacturing. *Structural and Multidisciplinary Optimization*. 2018 Jun;57(6):2457–2483.
- [11] Hardt DE. Modeling and control of manufacturing processes: Getting more involved. *Journal of Dynamic Systems, Measurement, and Control*. 1993 Jun;115:291–300.
- [12] Spears TG, Gold SA. In-process sensing in selective laser melting (SLM) additive manufacturing. *Integrating Materials and Manufacturing Innovation*. 2016 Dec;5(2):1–25.
- [13] Reutzel EW, Nassar AR. A survey of sensing and control systems for machine and process monitoring of directed-energy, metal-based additive manufacturing. *Rapid Prototyping Journal*. 2015;21(2):159–167.
- [14] Jacobs PF. *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography*. Dearborn, MI: Society of Manufacturing Engineers; 1992.
- [15] Pellegrino J, Makila T, McQueen S, Taylor E. Measurement science roadmap for polymer-based additive manufacturing. Gaithersburg, MD: National Institute of Standards and Technology; 2016. NIST AMS 100-5.
- [16] Craeghs T, Bechmann F, Berumen S, Kruth JP. Feedback control of Layerwise Laser Melting using optical sensors. *Physics Procedia*. 2010;5:505–514.
- [17] Mani M, Lane B, Donmez A, Feng S, Moylan S, Fesperman R. Measurement Science Needs for Real-time Control of Additive Manufacturing Powder Bed Fusion Processes. National Institute of Standards and Technology; 2015. NIST IR 8036.
- [18] Nassar AR, Keist JS, Reutzel EW, Spurgeon TJ. Intra-layer closed-loop control of build plan during directed energy additive manufacturing of Ti6Al4V. *Additive Manufacturing*. 2015 Apr;6:39–52.
- [19] Yoshikawa A, Narahara H, Suzuki H. Research on the uneven measurement on the liquid surface of photoresin in the stereolithography. *Journal of the Japan Society for Precision Engineering*. 2003;69(10):1434–1438.
- [20] Lu L, Zheng J, Mishra S. A Layer-To-Layer Model and Feedback Control of Ink-Jet 3-D Printing. *IEEE/ASME Transactions on Mechatronics*. 2015 Jun;20(3):1056–1068.
- [21] Hoelzle DJ, Barton KL. On Spatial Iterative Learning Control via 2-D Convolution: Stability Analysis and Computational Efficiency. *IEEE Transactions on Control Systems Technology*. 2016 Jul;24(4):1504–1512.
- [22] Tang L. Layer-to-layer control of laser metal deposition processes [PhD Thesis]. Missouri University of Science and Technology; 2009.
- [23] Cohen D, Lipson H. Geometric feedback control of discrete-deposition SFF systems. *Rapid Prototyping Journal*. 2010;16(5):377–393.
- [24] Garanger K. Introducing the foundations of a general framework for closed-loop control in additive manufacturing via in situ measurements and semantic annotations [Master Thesis]. Georgia Institute of Technology; 2018.
- [25] Wing I, Gorham R, Sniderman B. 3D opportunity for quality assurance and parts qualification. Deloitte University Press; 2015.
- [26] Cotteleer M, Trouton S, Dobner E. 3D opportunity and the digital thread. Deloitte University Press; 2016.
- [27] Everton SK, Hirsch M, Stravroulakis P, Leach RK, Clare AT. Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing. *Materials & Design*. 2016 Apr;95:431–445.
- [28] Ameta G, Moylan S, Witherell P, Lipman R. Challenges in tolerance transfer for additive manufacturing. In: *Proceedings ASPE 2015 Spring Topical Meeting*; 2015. p. 129–135.
- [29] Levine WS, editor. *Control system applications*. 2nd ed. Boca Raton: CRC Press; 2011.

A 5D DOF PARALLEL KINEMATIC CONTROLLER FOR BIG AREA ADDITIVE MANUFACTURING

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INTRODUCTION

The presented research includes controller and control strategies for 5D profiling in material extrusion based big-area assistive manufacturing. Current state of the art in additive manufacturing (AM) is primarily dominated by a 2.5D layered approach, that induce staircase effects on angled surfaces. This effect introduces manufacturing restrictions in terms of accuracy capabilities. Capabilities that may lead to the requirement of expensive extra process steps in the AM process to obtain the required surface finish of final part components [1]. In addition, the 2.5D layered approach further restricts the full 3D deposition movement required in many high strength continuous fiber composite components. Restrictions that prevent AM from venturing into high strength large scaled applications, with build envelopes above 1m.

In this initial study, investigations are made in the possibility of creating a five degrees of freedom (5DoF) controller system, for a material extrusion based machine. The investigation aims to show how this implementation might help the AM field to move from its traditional 2.5D AM (conventional layered approach) into true 3-dimensional AM.

METHOD

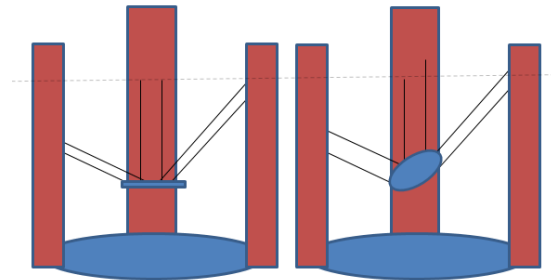


Figure 1: Schematic of parallel system and how the movement of the different arms can tilt the deposition head.

The material extrusion based system chosen for this demonstration is a parallel axis machine design, with a tailored inverse kinematic model, that forms the basis for the machine design [Figure 1].

The control system consists of three overall steps [Figure 2]:

- 1)** First step involves the conversion of the 3D CAD models into generic 5 axis G-codes known from e.g. CNC-milling.
- 2)** Second step is the conversion of 5 axis G-codes in the Cartesian coordinate space to a 6-axis machine specific coordinate space.
- 3)** Last step is the implementation of this code in the machine setup to enable the true 3D additive manufacturing.

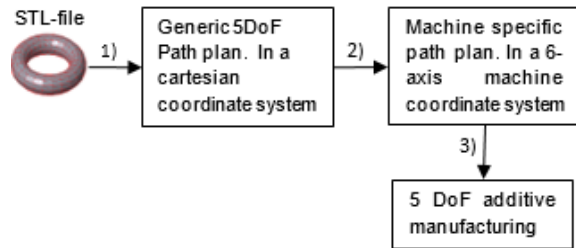


Figure 2: Overview of sequences of the control system.

The 5DoF path-planning of the CAD model

The first step in this sequence is to establish a generic way of getting the 3D CAD model information translated into 5DoF movement patterns.

For this initial study it is done by making a small piece of software aimed at interpreting the STL point clouds. In sequence; the STL data is brought into the software, wherein specific points and normal vector orientations are stored. Then the stored data points are sequenced in a pattern according to an overall process plan, as it is typically seen in different slicing software [Figure 3].

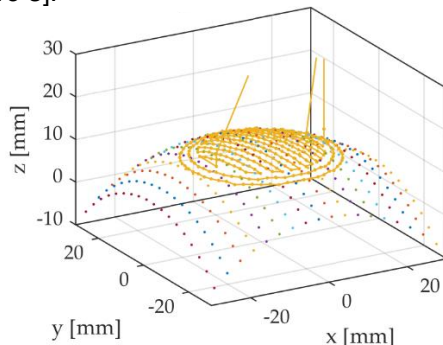


Figure 3: Illustrations of the point cloud and planned process sequence.

Instead of inventing new ways of developing the more generic slicing software from scratch, future studies should map out conventional CNC-milling CAM software to show how it can be integrated in a AM path-planner. The idea being that the CNC-planners have already dealt with many of the issues a 5DoF AM path-planner would experience [2]. Hereby attention can be brought to the ideal setup for making path-plans follow specific function force-pathways in 3 dimensions. This could for example be an additional step of making multiple surfaces of the solid body, spanning in the directions of the desired force pathway. The core of the part in the strength direction hereby become layer one. Layer two is placed on the surface of the first

and so forth. By the end of this initial step a complete sequence of cartesian points with respective normal vectors to the surface is created from a CAD model.

The inverse-kinematics model

The next step is the conversion from cartesian coordinates to 6 axis machine coordinates. This is done as shown in the flowchart below [Figure 4]. In this inverse-kinematics model deposition points and orientation from the path-planning software is converted to tower positions through geometric vector operations. The calculations are constraint so that build plate twists are removed and so that positions below the tool-head are never a result.

In the end of this step; six tower coordinates are given for each position input which is saved in a generic machine code format.

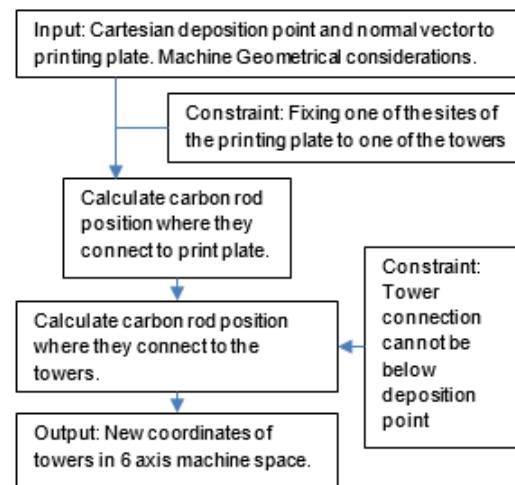


Figure 4: Flowchart of the inverse kinematics model.

Machine implementation

The last step of this sequence is implementing the generated 6 axis machine space coordinates into the desired 5DoF movements. These movements are prepared in the software controller main-loop, where position coordinates are sequenced and the movements are prepared [Figure 5]. The movements of the servo motors and deposition are activated in a timer interrupt loop. This loop is sequenced with a frequency proportional to the feed-rate, to secure a precise movement pattern independent of the calculation speed of the micro-controller.

```

Void function MainLoop {
If BufferSpace is available {
  Receive G-command from file
  Calculate step sequence for movement and direction of
  all axes.
  Write info into buffer
  Request new line from file
}
}

Void TimerInterrupt(Feedrate) {
If Step != EndStep && Buffer == available &&
newbufferline==prepared{
  Send move signal to servo motors
  If Step== Endstep {
    current position =step
    Increase bufferead
  }
}
If Step== Endstep && newbufferline != prepared{
  Look at next bufferline
  Set new Feedrate
  Set direction on each axis
  newbufferline = prepared
}
}

```

Figure 5: Pseudocode of the motion planner implementation program for the 5DoF system.

EXPERIMENTAL VALIDATION

To validate this new 5DoF controller setup, test geometries are prepared to illustrate the new 5DoF capabilities. These test geometries are in the shape of a half sphere, to illustrate the sloped structure in multiple directions, while these types of structures are usually difficult to prepare using material extrusion AM. These spheres are hence made both through conventional 3DoF techniques and using the new 5DoF controller setup. This is done to illustrate the differences between the techniques and to illustrate whether the 5DoF system can improve the surface accuracy of these types of geometries. Both tested geometries contain a base 3DoF half sphere shape [Figure 6, blue], and the 5DoF test geometry then has its upper-layers interchanged with a 5DoF path [Figure 6, red]. This path is following the normal to the spherical surface, which is planned by the previous mentioned process [Figure 7].

Before performing the test prints the movement sequences was performed in the middle of the build plate to verify the movement without the risk of breaking into the build plate.

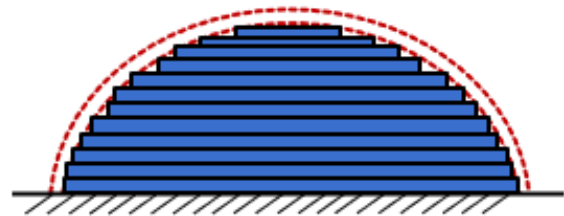


Figure 6: illustration of the half sphere test subjects seen from the side

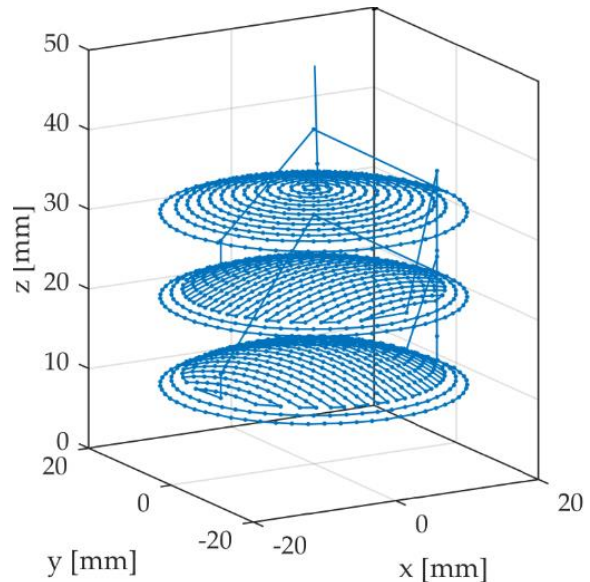


Figure 7: path planned by the previous mentioned process.

The controller setup is in this initial study tested on a 1.5m*2m(D*h) parallel kinematic system to verify its ability to execute the desired commands. The test geometry results are validated using high-resolution 3D scans from a 3Shape D800 3D scanner. The data is treated using 3Shape Convince 2015 Analyzer software that allows direct comparison between measured results and the desired CAD model used for the experiment.

RESULTS

Through these initial tests qualitative coherence between desired and actual movements in all directions are seen, hereby verifying the used approach [Figure 9].



Figure 8: Results of the printing process on the parallel kinematic machine without any post processing. Left: shows the normal 3DoF manufacturing. Right: shows the 5DoF implementation.

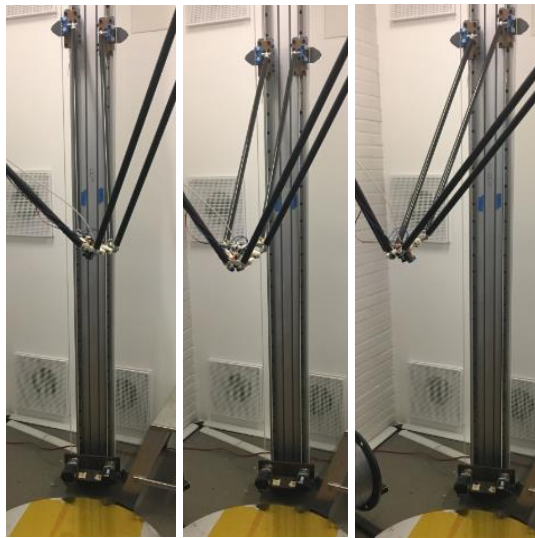


Figure 9: Picture sequence of the system performing 5DoF movements.

After the initial verification exercises, the experimental work ventures into the initial prints of the halved spherical surface [Figure 8]. These prints show visual accuracy improvements in the 5DoF prints, compared to the 3DoF prints [Figure 10]. Considering the individual prints from a side view scan, it is seen that certain deviations from the ideal geometry has occurred. On the 3DoF print, the stair chase geometry known from typical material extrusion based AM systems, is seen. This staircase effect is almost removed entirely in the 5DoF print.

When the samples are compared from above the deviation patterns from the ideal geometry are also showing significant improvements [Figure 11]. It is seen in the 3DoF print that many of the centre depositions are red (deviations above 1mm). The red color indicating print heights lower than the ideal CAD geometry.

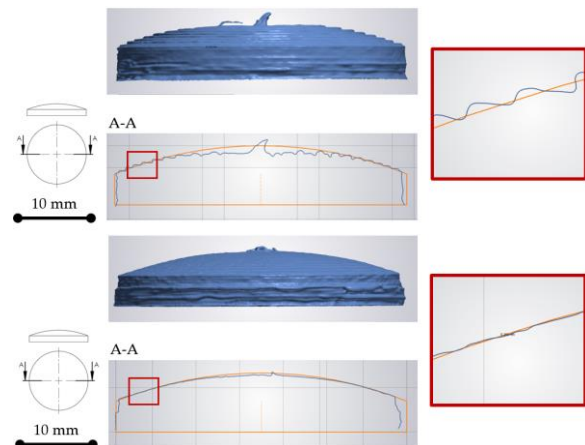


Figure 10: comparison between the CAD model and the actual prints. Top) 3DoF print. Bottom) 5DoF print. Red line shows the ideal CAD geometry.

This is to be expected from the incremental nature of the slicing software, which builds upon layer height increments. Increments that cannot accommodate for actual height differences in a slow increasing surface. Looking at the 5DoF print it is seen at it follows the surface geometry much closer especially in the center region, where most is green (deviation below 0.1mm) or blue/yellow (deviation below 0.2mm). In this picture it is though seen that the outer layers seem to be off. This feature might be a machine and/or a parametric setting feature, while the kinematics system has not yet been fully calibrated and validated. It could also be differences in the CAD descriptions given from the inverse kinematics model. Further studies need to be performed to investigate this phenomenon. But these prints show that the proposed 5DoF approach can produce smoother rounded surfaces than conventional methods. By adding the tilting of the tool-head it can more accurately reproduce the CAD geometry even at

increasing layer heights and it is equally importantly capable of smoothing out the staircase effects of previous layers made through normal 3DoF depositions.

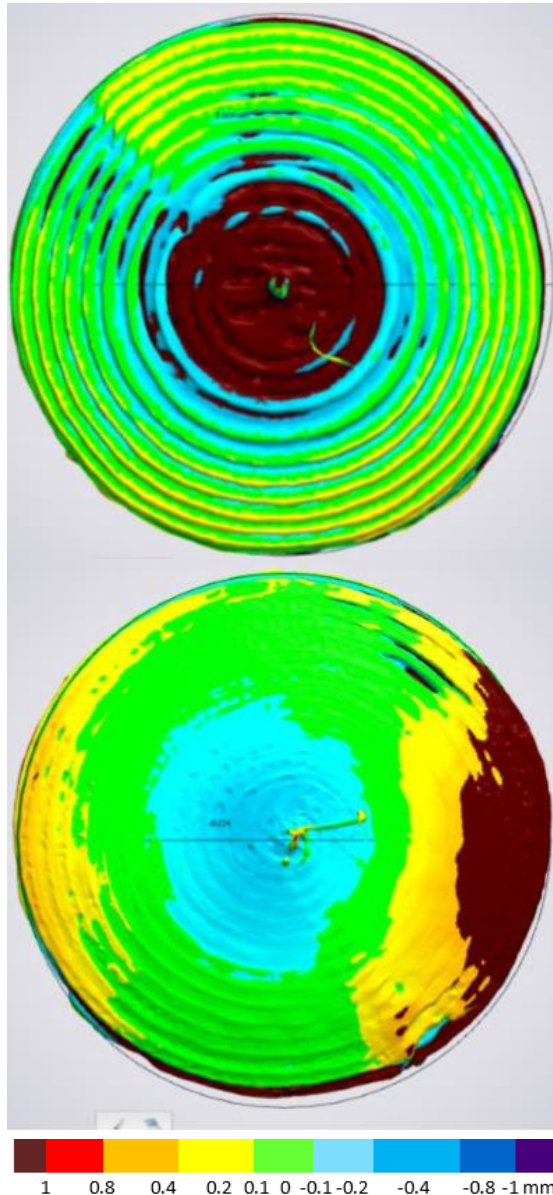


Figure 11: 3D scanned image Comparison between Top) the 3DoF print and Bottom) the 5DoF print.

In this way the results shown during this section indicates that the 5 DoF approach suggested by this study can improve the surface quality of AM produced parts. Even though issues are also found in this initial setup and further studies are to be made to increase the accuracy of each

aspect in this new AM approach. Further validation of the process chain needs to be made and the system accuracy and robustness needs to be fully tested and benchmarked.

CONCLUSION

This initial study has shown a controller setup and process pathway capable of converting CAD models into 5DoF movements of a parallel axis machine. This system aims to create a 5 DoF, platform capable of performing material extrusion based AM. So far, the setup movements have been verified, and initial prints have shown the imminent improvement made by the process. In this study it was found that the suggested 5DoF pathway decrease the center deviations of a halved spherical test geometry from 1mm to 0.1-0.2mm. Overall improvements were seen in the entire span of the test subject by the removal of the classical staircase effects known from typical extrusion based AM. Some larger deviations were though seen in the outer perimeter of the 5DoF prints, which origin of this specific error must be further studied.

The suggested controller setup of this study hence proved capable of manufacturing 5DoF parts, which further studies must show the increased value of.

REFERENCES

- [1] Hoeren K.P.J., Witt G. Design Opportunities and Limitations on Additive Manufacturing Determined by a Suitable Test-Specimen. In: Kovács G.L., Kochan D. (eds) Digital Product and Process Development Systems. IFIP Advances in Information and Communication Technology, Springer, Berlin, Heidelberg 2013; 411; 138-152.
- [2] Xu X.W., He Q. Striving for a total integration of CAD, CAPP, CAM and CNC, Robotics and Computer-Integrated Manufacturing. 2004; 20; 101–109.

A BEAM MODULATOR AND GALVANOMETER CONTROLLER FOR METAL POWDER BED FUSION

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INTRODUCTION

Powder-bed fusion [1] differ from conventional manufacturing processes not merely from the characteristics of the layered consolidation of matter from a powdered feed-stock. To an equal extent powder-bed fusion systems are barring from conventional machine tools in that they are of a highly proprietary nature. This counter the dilating understanding of the mechanisms governing the consolidation of metal powder particles in a powder bed fusion setup, as the research scientist is rendered a mere operator of the system from limits drawn by the manufacturer that prohibit full access to the machine controller and to feed-stock sources. From this, the research scientist is faced with a black-boxed manufacturing system which is strongly influencing the direction of research that can be conducted towards validation and characterization of said closed proprietary systems.

Disputing this, the Technical University of Denmark has in recent years established a research infrastructure for powder-bed fusion to separate with the operator limitations found in industrially available systems. This paper presents a laser modulation and galvanometer control unit that can unshackle the beam control system in powder-bed based systems, Figure 1 and thus allow for full control of the beam. The control unit is comprised of a hardware controller, its embedded firmware and an interface to a host-side job-planner, all of which has been tailored to experimental powder-bed fusion, allowing the research scientist to freely explore scan strategy, pulse modulation, speed, laser power, beam shaping and will be capable of cross-talk to industrial PLC's and controllers for NC stages such that the powder-handling system can be unshackled as well.

SYSTEM

The beam modulator and galvanometer controller is the subsystem in a powder-bed fusion platform that modulate the laser power through generation

of a signal sent to the laser unit in addition to controlling the position of each galvanometer mirror, by sending positioning signals to the galvanometer drive circuits. Said units; the laser and galvanometer drivers; are readily available as standardised industrial units that can be acquired to specifications whereas the beam modulator and galvanometer controller is a specialised unit associated with high acquisition expenses and complex interfacing protocols. The beam modulator and galvanometer controller presented in this paper outpace these specialised units by providing the researcher with a simple, flexible and cost efficient solution without compromising the performance of the unit.

The simplicity, cost effectiveness and performance is to a large extent achieved due to the advances in micro-controller computing power, communication protocol bandwidth and feature richness that now accommodate for algorithmic implementation of signal generation that formerly was required to be implemented as analogue sub-circuitry. The implementation and considerations hereof is as presented in the following.

GALVANOMETER CONTROLLER BOARD

The galvanometer controller unit has been designed such that it is to serve to receive angular mirror positions and laser modulation parameters from a host computer over a high-speed USB interface and from this generate the appropriate control signals to the interfaces available on the laser and galvanometer subsystems, see Figure 1. Most industrial fibre lasers can be modulated from an analog 10V control signal as well as most analog galvanometers can be interfaced with an analog ± 10 V control signal. For the specific application case of the galvanometer control unit in this paper, the laser is an SPI SP-250C-0003-000 [2] laser in high-spec configuration that can be modulated at 100kHz and the galvanometer system is a Thorlabs GVS012[3]. In the following sections an overview of the galvanometer controller board is given and the control signal

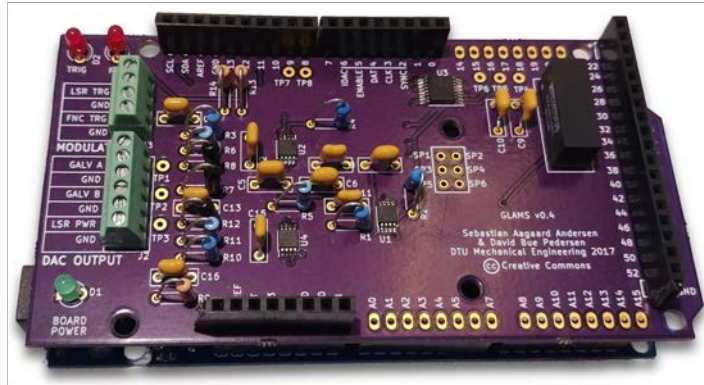


FIGURE 1. Galvanometer control unit tailored to control and modulate the laser unit and position the galvanometer mirrors in order to control the process of metal powder bed fusion.

generation pipeline is detailed.

Micro Controller Unit

To meet the modulation requirements of high-spec fibre lasers and analog galvanometer systems, a high-performance 32 bit Atmel SAM3X8E Cortex® M3 RISC® ARM® processor is used, boasting a 84 MHz clock, 512 Kb flash and 100 Kb SRAM, [4]. The processor peripherals used in the galvanometer control unit are its internal High Speed USB Host and embedded transceiver, Universal Asynchronous Receivers/Transmitters (UARTs), and Serial Peripheral Interfaces (SPIs), as well as built-in pulse width modulation (PWM) timer, general-purpose 32-bit timers 12-bit analog to digital converter (ADC) and a 12-bit digital to analog converter (DAC).

The USB interface and UART are hardware implemented and therefore does not excerpt from the computational load of the SAM3X8E. These are used to provide for a high-bandwidth communication to a computer host with a transmission capacity that can accommodate real-time updates of the gross of the galvanometer position signals and the laser modulation signal at 100kHz. The hardware implemented SPI bus, as with the USB interface, does not excerpt from the computational load of the SAM3X8E and is used to update a four-channel digital to analog converter (DAC) that consecutively generates analog output that is to be amplified and used as outputs for the laser and galvanometer driver units.

Digital to Analog Converter

The orientation of the dielectric scanner mirrors, mounted in the galvanometer system applied in in the experimental setup, is given by an $\pm 10V$ analog control signal. To obtain this signal from the inherently digital micro controller, the digital signal has to be converted with a DAC to an appropriate analog signal. Resolving this signal with a resolution that yields appropriate manoeuvrability, the 12-bit internal DAC of the SAM3X8E controller is insufficient. An external DAC8564 [5] 16-Bit, Quad Channel, Ultra-Low Glitch, Voltage Output DAC with 2.5V, 2ppm/°C Internal Reference from Texas Instruments is interfaced using the SPI bus of the SAM3X8E controller. The DAC8564 yield a resolution of; $2^{16} = 65,536$. As the position of the DAC is set, as governed by the following equation:

$$V_{out} = V_{ref} \cdot \frac{D_{in}}{65536} \quad (1)$$

V_{ref} is the reference set to 2.5 V, and D_{in} , is the decimal number equivalent of the binary code transmitted to the DAC. Giving a maximal analog signal of 2.5 V, when $D_{in} = 65536$.

Operational Amplifiers

As described in the previous section, the DAC8564 has a voltage output range of 2.5v. This is below the voltage signal range of $\pm 10V$ that most industrial analog galvanometer systems accept. Therefore the voltage output is amplified using Operational Amplifiers (OPAMP). The OPAMP circuit is based upon a reference design from Texas Instruments [6] that specifically is intended

for generating voltage outputs commonly used in industrial process control applications and for driving reactive loads such as long cables. The OPAMP circuit of the controller unit is based upon the OPA188 operational amplifier and exhibits a low offset voltage of maximum 25V and has near zero-drift characteristics. [7] The performance of the OPAMP circuit is shown in table 1.

TABLE 1. Monte Carlo Simulated Circuit Performance assuming 0.1% component tolerances [7]

Parameter	Simulated Value[6]
Offset Error (% FSR)	0.200
Gain Error (% FSR)	0.112
INL Error (% FSR)	0.012
Total Unadj. Error (% FSR)	0.230

Interface

The Galvanometer Controller Board is designed to give an easy overview over the different interfacing capabilities. In Figure 1 the screw terminals, is labelled so that the signal wires can be mounted to the modulation section containing two transistor-transistor-logic (TTL) outputs aimed at triggering the laser and a function generator or another TTL compatible subsystem. Both of these TTL signals will trigger a diode, allowing testing without actual laser interfacing. Mounting signal wires to the terminals in the DAC OUTPUT section, will give the control signal to the two individual galvanometers, and the laser power control.

IMPLEMENTATION

The viability of the galvanometer controller board is tied to both the understanding the hardware summing up the powder-bed fusion machine tool and the computation required to accurately drive and replicate a given 3D geometry. These different subsystems and routines are described in this section.

Galvanometer

The galvanometer has a maximal angular deflection of $\pm 20^\circ$, with a positioning signal of ± 10 V, scaled to with the lowest possible scaling factor: $0.5 \text{ V}/^\circ$. Other possible scale factors are $0.8 \text{ V}/^\circ$ and $1 \text{ V}/^\circ$ allowing a lower scan range, but a higher angular resolution. Limited at increments of 0.0008° [3], as the capabilities of the galvanometer board surpasses this limit by providing increments of $20^\circ/65,536 = 0.00031^\circ$, the highest resolution is obtainable.

Laser

The laser implementation allows control of a modulated or continuous wave (CW) laser beam at maximum 250 W. The operational state of the laser can be set remotely from the galvanometer controller board, requiring a TTL signal. Transmitting either a constant signal or pulse width modulated (PWM) signal will put the laser in wither CW or modulated mode.

Manoeuvring the level of power emitted from the laser is done by an analog 0-10 V signal, and is obtained by a the DAC and a slight change to the OPAMP configuration, providing in-situ operability of the laser.

Firmware & job planner

Governing the powder-bed fusion machine tool is done by a custom firmware developed for the galvanometer controller board. Figure 2 draws out the different stages handled in the firmware. From the command is received a range of calculations is done, and the laser is set while the mirrors move to accompany the desired pattern. The firmware implemented takes standard g-code commands [8] with the addition of a few laser specific machine code (m-code) commands.

Taking advantage of the resolution provided by the setup the speed of which the cycle displayed in Figure 2 can be handled effectively determines the speed at which the mirrors can be incremented. Due to the 84 MHz clock speed of the 32 bit Atmel Micro Controller the entire algorithm shown in Figure 2, can be conducted in $29 \mu\text{s}$. Hence a full range scan at the highest resolution provided by the galvanometer unit, will take $65,536 \cdot 29 \mu\text{s} = 1.9 \text{ s}$. As the resolution of the galvanometers is limited to 37,5% of the capabilities provided by the control unit, the actual time for a full scan will be 0.7 s. In the current setup this will yield a theoretical maximal speed of 254 mm/s. Calculating the possible scan distance from Equation 2 [3] where f is the focal length of scan lens and θ_{max} is the maximal scan angle in radians. Giving a diagonal length of the scan field, L of 178 mm.

$$L = f \cdot 2 \cdot \theta_{max} \quad (2)$$

The job planner is written to take a 3D geometry and process it into a layer-wise pattern, then convert it into gcode commands. To increase the usability of the planner a graphical user interface

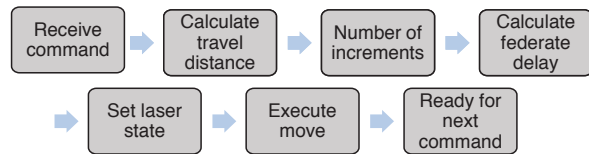


FIGURE 2. Computation flow of the received commands, conducted on the Galvanometer Controller Board

allows adjustment of hatch lines spacing, laser power, scan speed and more, see Figure 3.

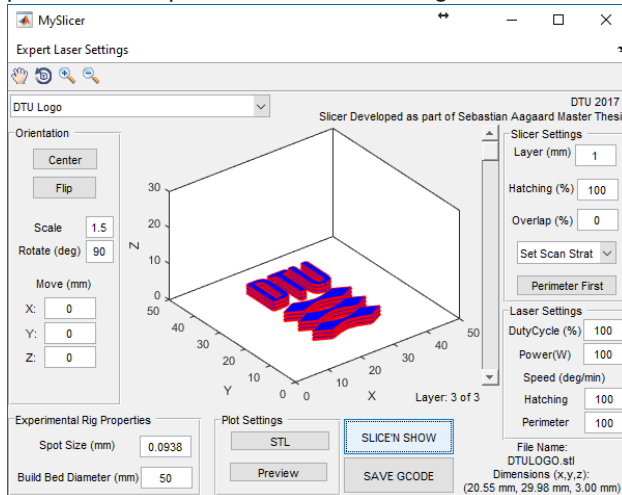


FIGURE 3. Graphical user interface of the custom jobplanner.

EXPERIMENTAL VALIDATION

The hatch lines displayed in Figure 4, shows the initial test with the new setup, here it becomes obvious that the custom platform is capable of delivering uniform hatch lines with adequate hatch line spacing. Further tests will display how different operational settings of the laser will affect the consolidation.

Geometrical Replication

The geometrical replicability of the desired geometry has been tested with a hole plate test, where 5 x 5 identical holes has been engraved across the scan field[9]. Figure 5 displays the offset found from the theoretical positions, along the x axis the maximum offset is found at the top-left corner, 0.79 mm, and along the y axis maximal deflection is at the centre bottom point, 0.33 mm. The measurements was obtained on the optical microscope DeMeet 220.

Process Parameter Study

Utilising the beam modulator and galvanometer controller for metal powder bed fusion. An experimental setup that allows single layer powder

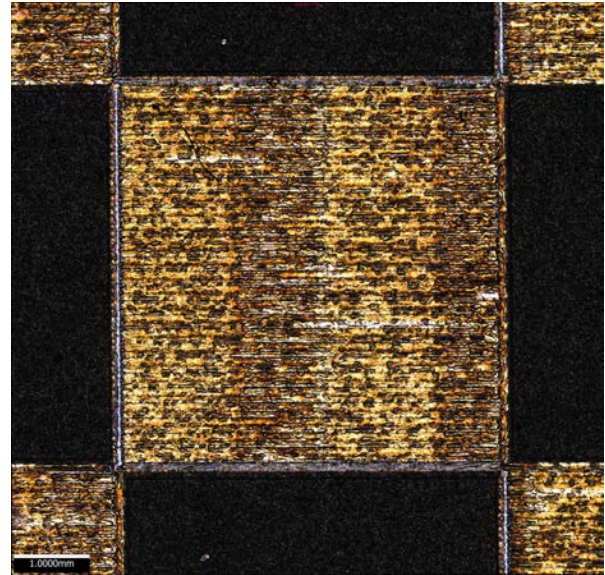


FIGURE 4. Uniform hatch lines as a consequence of utilizing the platform developed for a powder based additive manufacturing machine tool

distribution, brings the research to an initial stage where the consolidation process can be carefully controlled and the process conditions monitored.

A maraging steel from EOS, MS1, has been used to conduct single layer consolidation experiments. A brief experimental campaign has been carried out, revealing the response from the melting process, see Figure 6 and process parameters in Table 2.

CONCLUSION & PLANNED DEPLOYMENT

This work has presented the design considerations, physical implementation and preliminary validation of a beam modulator and galvanometer controller for metal powder bed fusion. In its implemented form, from Monte Carlo simulation of the error of the controller system, it has been shown that the controller error will not exceed 2.3%. The controller system allow for the generation of a dual ± 10 V control signal for analog galvanometers at a 0.00031° resolution and a 0-10V analog laser modulation control signal with a resolution of 0,1525mV. An experiment was set up by which the galvanometer and beam modulator controller was validated through the engraving of a checker-board pattern. The test indicated that the maximum distortion of the image field was in the magnitude of 0.79mm. This distortion has been attributed to the barrel-and pincushion distortion found in F-theta lenses.

TABLE 2. Experimental parameters used in the Figure 6.

Scan Speed [mm/s]	Power [W]	Layer [mm]	Energy Density [J/mm ²]
40.5	150	0.1	37.04

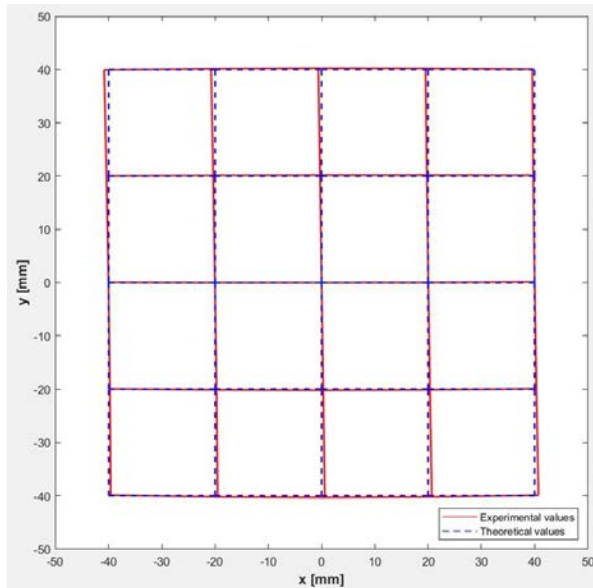


FIGURE 5. Offset of the actual positions of the laser across the scan field. Dotted lines show the intended theoretical positions, red lines displays the measured positions.

The geometrical replication still requires calibration, as the optical system does not imply linear distortions, focus is being shifted to correcting the values applying a lens correction algorithm.

Current work is going into bench-marking the galvanometer and the response from the powder bed fusion process. The consolidation process of the metal powder particles, displays well-known phenomena as balling and reintroduction of ejected particles onto the surface of the ejected particles. Revealing that process parameters are readily changeable by the beam modulator and controller unit.

Shown in this article the application of the tailored beam modulator and galvanometer controller for metal powder bed fusion systems is apparant, and the tasks that can be solved with such a device has the potential to be on par with industrial grade systems. During the calibration and construction of the controller and the software a lot of knowledge about communication protocols, move algorithms and other subroutines was earned. As

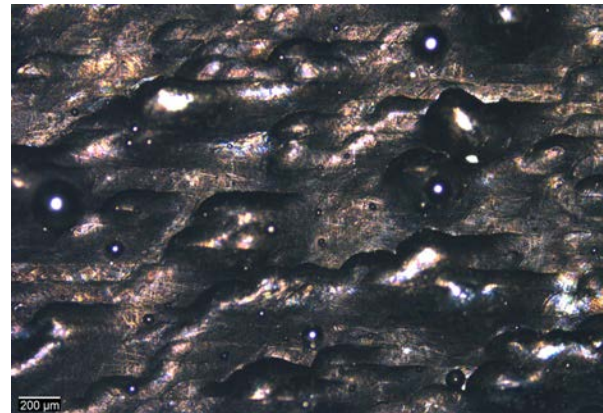


FIGURE 6. Deploying the Galvanometer Controller unit to consolidate metal powder particles, the material is Maraging Steel, MS1 EOS, process parameters found in Table 2

the controller rapidly comes to an implementation level where an actual powder bed can be introduced with layer onto layer capabilities, and the obtained parts has to be fine tuned, the pay off from not going with proprietary solutions yields a deep understanding, and full flexibility to alter the beam trajectory, move algorithm or any other parameter of the setup.

References

- [1] "ISO/ASTM 52900:2015. Additive manufacturing - General principles - Terminology," International Organization for Standardization, Geneva, CH, Standard, Dec. 2015.
- [2] *Product manual: R4.3 high power fibre laser systems - hs*, SM-S00393, Rev. C, SPI Lasers UK Limited, 6 Weelington Park, Hedge End, Southampton, SO30 2QU, UK, Apr. 2015.
- [3] *User guide: Large beam diameter scanning galvo system*, 15th ed., HA0220T, Thorlabs Incorporated, 56 Sparta Ave, Newton, NJ07860, USA, Nov. 2017.
- [4] *Sam3x / sam3a series atmel smart arm-based mcu*, 11057C, Atmel Corporation, Mar. 2015.
- [5] *DAC8564 datasheet*, Rev. SBAS403D, Texas Instruments Incorporated, Jun. 2011.

- [6] K. Duke, *Ti precision designs: Verified design bipolar+/-10v analog output from a unipolar voltage outputdac*, SBAS403D, Texas Instruments Incorporated, Post Office Box 655303, Dallas, Texas, 2014.
- [7] *Datasheet: OPA188*, SBOS642B, Revised Sep 2016, Texas Instruments Incorporated, Post Office Box 655303, Dallas, Texas, Mar. 2013.
- [8] "ISO 6983-1:2009. Automation systems and integration - Numerical control of machines - Program format and definitions of address words - Part 1: Data format for positioning, line motion and contouring control systems," International Organization for Standardization, Geneva, CH, Standard, Dec. 2009.
- [9] H. Hansen and L. De Chiffre, "A combined optical and mechanical reference artefact for coordinate measuring machines," eng, *Cirp Annals - Manufacturing Technology*, vol. 46, no. 1, pp. 467–470, 1997, ISSN: 17260604, 00078506.

Metal Additive Manufacturing: from the generation of surfaces to their functionality

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INTRODUCTION

Additive Manufacturing (AM) techniques provide new insights and outlook for industry. Indeed by adding material layer by layer, AM allows to create complex geometries which could not be built by conventional subtractive methods. The following advantages can be mentioned: no restriction on design for potential weight reductions. Also, design changes can be performed rapidly and do not require important process changes as for conventional manufacturing. Furthermore, near net shape process could create less waste. Finally, difficult to cut materials are easily processed with AM. Therefore aerospace and bio-medical industries are especially interested in developing such technique since high performance materials (Titanium alloys, stainless steels, Inconel) can be used.

Among additive manufacturing processes, Selective Laser Melting (SLM) also referred as Laser Powder Bed Fusion provides fine geometry precision. However compared to conventional manufacturing processes, surface topography quality is still one of the drawbacks and needs more detailed studies for optimisation purposes.

AIM OF THE STUDY

The following article proposes to investigate topographies generated by Laser Powder Bed Fusion (also known as SLM). A detailed study of form and roughness parameters is performed to emphasize different surface generation phenomena for different inclination angles. This study does not tackle the influence of process parameters but only the influence of building inclination angles on generated topographies.

Samples generated using optimum laser parameters are made from Ta6V powder.

Different inclinations of samples are generated to simulate local slopes which could be observed for complex objects. Upskin and downskin surfaces are therefore possible to analyse and a wide range of scales is studied thanks to different measuring techniques. The literature found in this field often focus only on average roughness Ra. By a detailed study, several roughness parameters are proposed to be relevant for process evaluation. Indeed different surface generation phenomena can be emphasized and modelled. The potential functionality of such surfaces (as-built or finished) is also discussed.

MATERIAL AND METHODS

Test specimens: as built SLM samples

Concerning AM samples, all the specimens have been produced on the same construction plate (see figure 1) according to the following procedure:

The Ti-6Al-4V powder from TLS Technik has the following granulometry: $Dv_{10}=7.6\ \mu\text{m}$, $Dv_{50}=28.6\ \mu\text{m}$, $Dv_{90}=41.9\ \mu\text{m}$. The production is performed with virgin powders under Argon. The machine is a ProX® DMP 200 and optimized parameters (Laser power, scan speed, hatch spacing, layer thickness) are used to obtain an energy density $Ed=79.4\ \text{J/mm}^3$ which gives an optimized porosity level.

The scanning strategy is based on a trajectory of the laser going back and forth. The scan direction is shifted of 90° from one layer to the other. No hexagonal or contour strategy is used in order to have the most basic topography patterns which can be generated by the process. The test specimens (20 by 20mm surfaces) are designed with inclinations from the substrate plate going from 0° to 90° . As a consequence 15 surfaces (10 upskin and 5 downskin) are available. Downskin surfaces are built without

any support so that metal cutting operations can be avoided. As a consequence no downskin surface is built for inclination angles lower than 50° to avoid collapsing risks. The relative angle between the specimens and the coater is chosen to be 45° to diminish coater/part interaction.

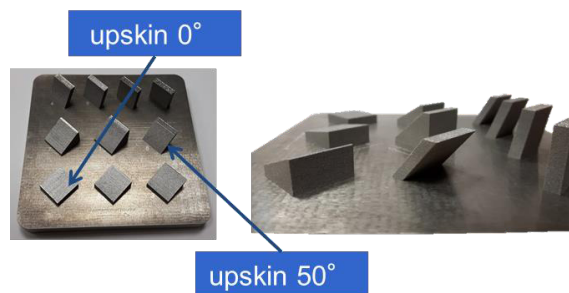


FIGURE 1. tests specimens produced by Laser Powder Bed Fusion.

Heat treatments are often chosen after AM to induce phase transformations and homogenize the microstructure. The SLM plate produced in this study has been heat treated to release stresses and homogenize the microstructure: 1 h at 940°C followed by furnace cooling with Argon and 2 h at 650°C. The specimens are dissociated from the plate by wire EDM after the heat treatment.

Surface topography characterization

A wide range of measuring instruments is used to observe topographies at different scales (see figure 2), from millimeter to micrometer scales:

- Coordinate measuring machine is used to observe the form of the samples: the CMM sapphire tip ($\phi=6$ mm) scans the total area of each sample with 64 coordinate measurements (8 by 8 points).
- Cross sections to observe the “real” 2D profile of surfaces.
- Contact stylus measurements (3 measurements per sample).
- Focus variation microscopy (see figure 2) is used (Infinitefocus G5). The 3D topographies are obtained with 20× magnification (lateral resolution: 2 μ m, vertical resolution: 50 nm). The area measured for each inclination sample was 3.22mm by 1.90 mm. The area measured is therefore able to catch more than 60 layers of the production and 40 weld tracks. As a consequence it is believed that one measurement is statistically relevant. 5 X magnification measurement is also

performed over the whole area of the 0° inclination sample.

The SLM specimens are therefore scanned at multiple scales: from form to roughness, from millimeter to micro/nano meter scale.

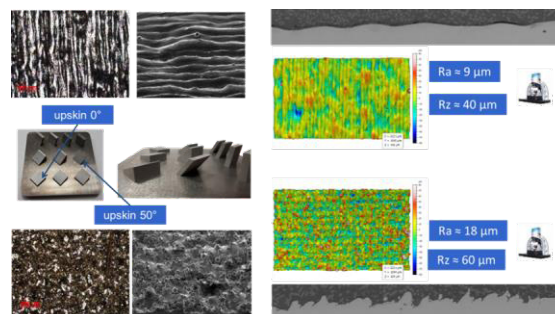


FIGURE 2. examples of topography measurements of surfaces generated from different inclinations.

RESULTS AND ANALYSIS

Comparison of measuring techniques

In this section the CMM technique is compared to a large scale focus variation measurement (5× magnification) of the whole 0° inclination sample. Figure 3 points out one of the drawback of CMM measurements: the area possible to measure is limited by the size of the sapphire tip. In the following case, the tip diameter is 6mm meaning that the first points measured are generally situated at 3mm from the sample's edge. As a consequence an important feature from AM samples is not caught: indeed at the sample edges a slight increase of weld track size is observed by the focus variation measurement. This is due to the melt pool hydrodynamic which generates a larger bulk at the edges (see figure 3).

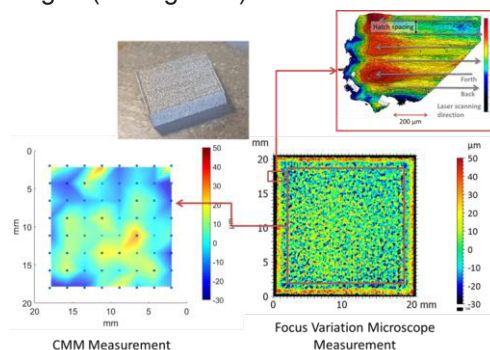


FIGURE 3. CMM measurement versus FV 3D measurement.

Identification of roughness parameters relevant for process evaluation

A detailed study of areal roughness parameters as a function of sample inclination is proposed in this section. The 3D topographies are characterized with areal roughness parameters which were computed thanks to MountainsMap® Premium 7.4.9. Non measured points were filled in (the measurements contain 0.8% of non-measured points in average) and a polynomial filter of order 2 was chosen to remove the form. It is important to notice that no other filtering was performed for 3D surfaces. Indeed no specific reason exists so far to dissociate waviness from the measured signals. Furthermore, classical filters and cut-offs usually applied on surfaces obtained by conventional machining are difficult to transpose for AM surfaces.

A wide range of roughness parameters is computed from the preprocessed surfaces and includes the main families to better understand the surface generation. The following analysis can be performed:

- As expected the arithmetic mean height globally increases with the inclination angle and downskin surfaces are rougher (see figure 4). It is however difficult to get a deeper look on generated surfaces with this parameter. The following figures will help to better understand the surface generation phenomena.
- Concerning hybrid parameters: the increasing amount of partly melted particles make the surfaces generated more and more complex (see figure 5). Indeed there is a clear correlation between inclination angle and the fractal dimension S_{fd} . This parameter indicates a measure of the space filling capacity: S_{fd} of 2 being a flat plane and S_{fd} of 3 being a volume completely filled in.
- Concerning amplitudes: the skewness S_{sk} has a very interesting trend as the inclination increases (see figure 6). The parameter seems to follow a sinusoidal trend meaning that the staircase effect is visible with this parameter. Furthermore, downskin surfaces are negatively skewed surfaces whereas upskin are positively skewed. The skewness is therefore a discriminating parameter for AM surfaces. It is believed that this can be explained by the staircase shape as the inclination angle

increases: from 0° to 45° the staircase generates more and more protruding stairs (peaks) and from 45° this geometrical aspect is attenuated. For downskin surfaces melted material is attracted by gravity leaving a few deep valleys at each layer. As a consequence a negative skewness is obtained. The trends are indeed sinusoidal and models could be built in future to express the staircase effect in the AM surface signature.

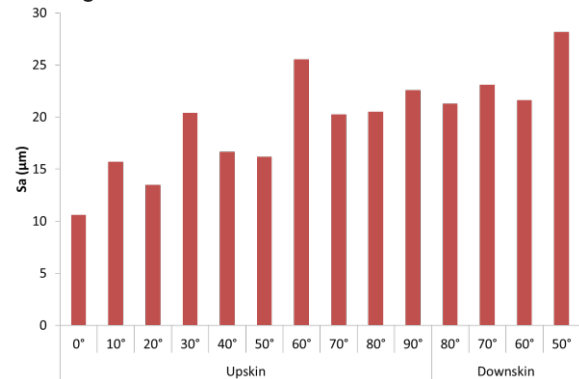


FIGURE 4. Areal arithmetic mean height S_a as a function of the inclination angle.

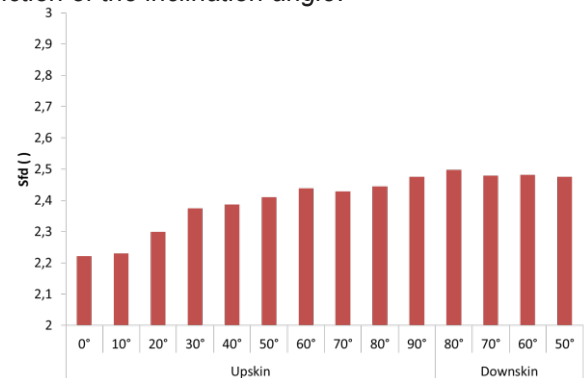


FIGURE 5. Fractal dimension S_{fd} as a function of the inclination angle.

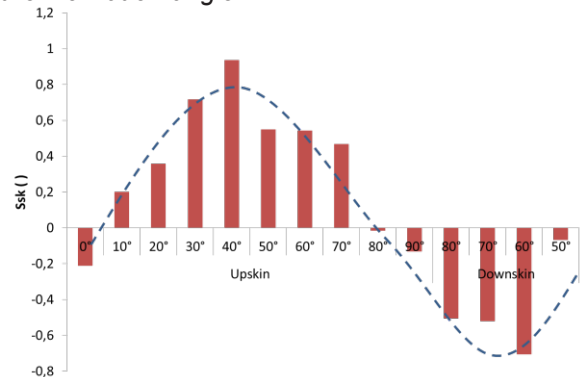


FIGURE 6. Areal skewness S_{sk} as a function of the inclination angle

Discussion on functionality and post processing

The previous analysis indicates that it is barely possible to imagine a direct use of AM as-built surfaces as functional surfaces. Two main reasons can be emphasized and should be taken into account when investigating the interest of different finishing processes:

- First of all as-built AM surfaces are rather rougher (S_a value higher than $10\mu\text{m}$). Furthermore the topographies obtained are very heterogeneous and depends on the inclination angle (see figure 8). As a consequence the finishing process might keep this heterogeneity if it does not remove enough material.
- The roughness level has a similar order of magnitude than the form error. This aspect means that a finishing process will both influence the roughness and the form.

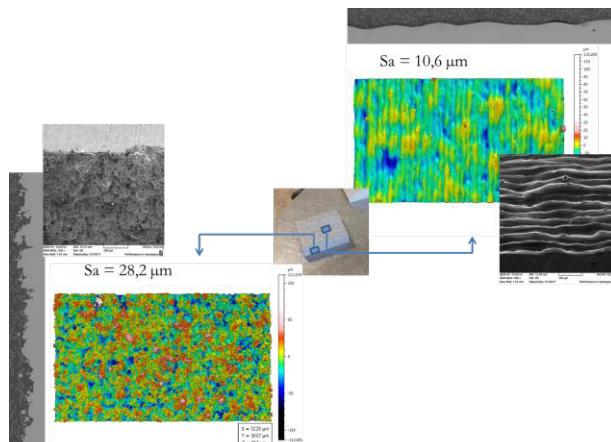


FIGURE 7. heterogeneity of surface roughness for as-built samples

CONCLUSION

The article investigated multi scale topographies (from form to roughness) of as built surfaces generated by a metal additive manufacturing technique: selective laser melting (SLM) or Laser Powder Bed Fusion (LPBF). Different building inclinations of samples were observed both for upskin and downskin surfaces with a wide range of measuring techniques. The main aims were:

- to enlighten the different surface generation phenomena (and their scale) occurring during the additive manufacturing

- to propose relevant roughness parameters for the process evaluation

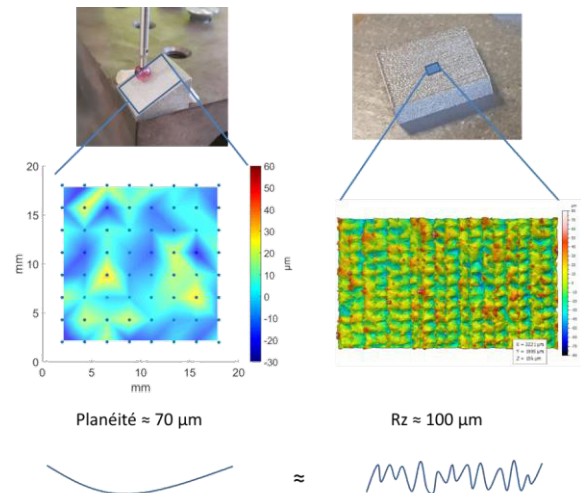


FIGURE 8. form error and roughness have similar orders of magnitude

The following conclusions were found:

- Identification of roughness parameters relevant for process evaluation: The skewness S_{sk} is a very interesting parameter which discriminates upskin and downskin surfaces. Indeed more peaks and less valleys are observed on upskin surfaces having positive skewness whereas less peaks and more valleys are observed on downskin surfaces having negative skewness. This parameter is behaving as a sinusoid with the inclination angle. It is therefore believed that it is able to distinguish the staircase effect inside a topography measurement. The differences observed between the different inclination samples are considered to be statistically relevant (S_{sk} variation of more than 200%). However it would be important to confirm the trends observed for more production plates. Furthermore it would be important to see if material changes lead to similar conclusions.

In future the important parameters found in this study will help to model precisely staircase effects and hatch spacing effects. Such defects are inherent to the AM processes and could be isolated in order to optimize more efficiently the processes. Finally this study is a starting point which will help to understand how to select the

appropriate finishing processes and their parameters so that functional surfaces could be obtained.

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REFERENCES

- [1] Bandyopadhyay A, Bose S. Additive manufacturing. CRC Press; 2015.
- [2] Gu D. Laser additive manufacturing of high-performance materials. Springer; 2015
- [3] Townsend, N. Senin, L. Blunt, RK. Leach, and JS. Taylor. Surface texture metrology for metal additive manufacturing: a review. *Precision Engineering*, 46:34–47, 2016.
- [4] Vrancken B, Thijs L, Kruth JP, Van J, Humbeeck. Heat treatment of Ti–6Al–4V produced by selective laser melting: Microstructure and mechanical properties. *J Alloys Compd*, 541:177–85, 2012.

EVOLUTION OF COOLING LENGTH IN PARTS CREATED THROUGH LASER POWDER BED FUSION ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufactured (AM) components, specifically those created through laser powder bed fusion (LPBF) methods, exhibit an abundance of surface textures of varying forms and patterns. These topographies have historically been categorized solely using their R_a values, a metric which offers limited information to discern differences among the morphologies of AM surfaces. This diversity is illustrated not only among parts made using different machines or processing parameters, but also between different locations in the build chamber and even on the same part. Current instruments have the potential to acquire three dimensional (3D) maps of the AM surface, enabling a range of field and feature based descriptors that offer potential in characterizing AM surface morphology. This work explores feature-based metrology of AM surfaces in an effort to relate features to part quality, as well as aid the modeling community in better understanding of melt pool geometry. The feature of interest in this work, the chevron pattern seen on top of scan lines, is theorized to be connected to the laser parameters used in the printing of the part. This research explores the chevron pattern, observing changes in this feature over a range of laser power and velocity combinations.

INTRODUCTION

Metal AM is a growing technology which fabricates parts directly from 3D computer aided design (CAD) models. Parts are built up layer-by-layer starting at the substrate. A single layer of

metal powder is deposited over the substrate and the first layer of the part is selectively melted, fusing with the substrate. The build plate is lowered, and the process repeats until the part is completed. The layer-by-layer building of these parts allows for them to be created with complex geometries not attainable through traditional manufacturing methods.

Though AM processes can create geometries that other methods cannot, they are not without their own disadvantages. Parts often take on the order of hours to days being built and suffer from poor “as-printed” surface quality. While finishing processes such as laser ablation or bead blasting can improve surface roughness [1-4], the increasing complexity of these parts can render these processes ineffective. These rough surfaces are a major hurdle in the full-scale implementation of AM [5], as the understanding of their morphology is still in its adolescence. Often, these complex surfaces were being categorized by their R_a values alone; however, it has been shown that these classical parameters prove to be similar for visibly different surfaces [6-9]. In previous works, the authors have shown that based on the areal average roughness (S_a), as well as other parameters outlined in International Organization for Standards (ISO) 27178-2 [14], that it is impossible to discern between two qualitatively different surfaces (Figure 1) [6]. Additionally, two works by Fox *et al.* launched an investigation into downward facing, as-printed surfaces. These works

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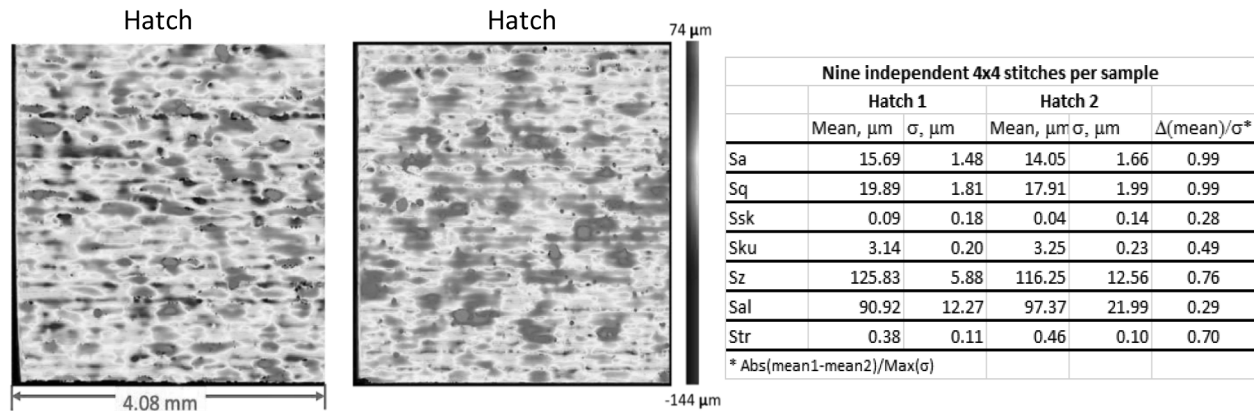


FIGURE 1. Comparison of two different metal AM surfaces based on ISO parameters

conclude that the use of R_a alone is insufficient in discerning the difference between surfaces predominantly covered by powdered metal particles and those dominated by scan tracks [7,8]. This has driven a push toward feature-based investigation for surface characterization. Rather, many researchers are beginning to rely on surface features to characterize metal AM parts [6-9].

With the previous standard method returning very little in the way of new surface information and a push toward feature-based investigation for surface characterization, the authors have identified the prominent chevron pattern that is often seen on upward facing surfaces of AM parts as a feature of interest (Figure 2). It is theorized that the chevron pattern may be linked to the dimensions of the melt pool.



Figure 2. Chevron pattern on upward facing surface of AM part

Preliminary work in numerical simulation has been performed in an effort to suitably model the melt pool dimensions for given build parameters. Gockel and Beuth have shown that, through finite element simulation, one can predict microstructure and grain morphology in Ti-6Al-4V. When operating in certain regions of the laser power-velocity (PV) process map, one can control the melt pool geometry and affect the cooling rate of single scan passes [10]. Other modeling attempts have explored this idea, for various nickel alloys rather than titanium. Keller *et al.* simulated the laser melt pool in nickel alloy 625 using finite element analysis. Simulations matched the surface temperatures captured in-situ with thermographic measurements in order to approximate thermal conditions beneath the surface of the scan line. Understanding these thermal conditions will allow one to predict and eventually control microstructure during builds [11]. This work was further expanded on by Ghosh *et al.* extending the same numerical simulations to nickel alloy 718 [12].

EXPERIMENTAL SETUP

The first step in this feature-based metrological approach was to look at the scan lines that appear on the top of the build without outside influence from the rest of the surface. To make this case as simple as possible, a number of single scans without powder were printed to build knowledge about the scan lines themselves. Single scans were printed into a nickel alloy 625 substrate in an EOS M270 Direct Metal Laser Sintering (DMLS) machine. These scan lines have a chevron pattern that occurs on the top of each line and is qualitatively different between scans of different PV combinations (Figure 3). Given this variation in the pattern, the angle

between the legs of the chevrons was chosen as a metric to quantify these variations.

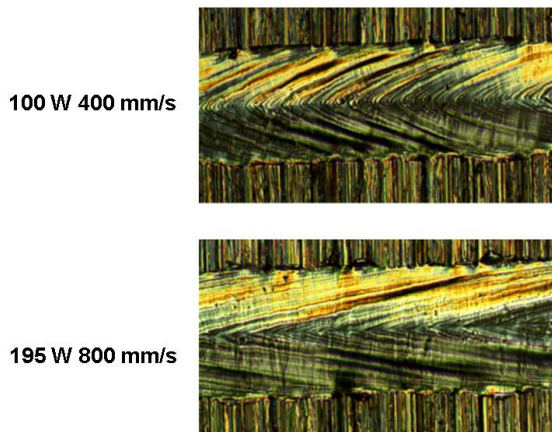


FIGURE 3. Variation in chevron pattern between different laser power and velocity combinations

If one knows the angle of this pattern and the width of the scan track, it is trivial to back out the length of the melt pool from its widest (and deepest) point to the tail. The length of the solidified melt pool from the tip of the chevron to the point where the legs reach the width of the scan line will be referred to as the “cooling length” (Figure 4). The importance of cooling length is described in another work by Gockel *et al.* who show that the cooling length is correlated with the microstructure of that track after cooling [12]. This information can potentially supplement the in-situ thermal data for validating models of melt pool dimension.

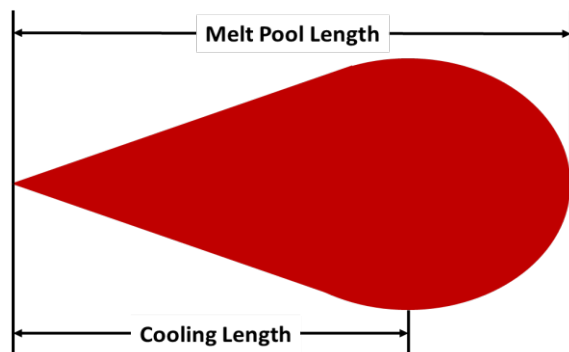


FIGURE 4. Distinction between melt pool length and cooling length

All builds for this paper were conducted in an EOS M270 DMLS machine. Six sets of 24 single pass scan tracks were printed over the course of two days to investigate the stability of this feature run to run as well as day to day. Each scan line is 10 mm long and offset by 2.5 mm from the

previous line. This ensures that the melt pool has sufficient time to reach steady state conditions in each line and is not influenced by the residual heat of the previous tracks. Power and velocity (PV) combinations are shown in Figure 5. Single scan lines ensure the chevron structure occurs in the middle of the track with little variation in the angle between the legs of each chevron. Printing with only beam on plate (i.e., no metal powder) mitigates any chance of spatter particles ejecting from the melt pool, denuding effects which can cause irregularity in the scan lines, partially melted powder particles adhering to the surface, and the variability of powder layer thickness.

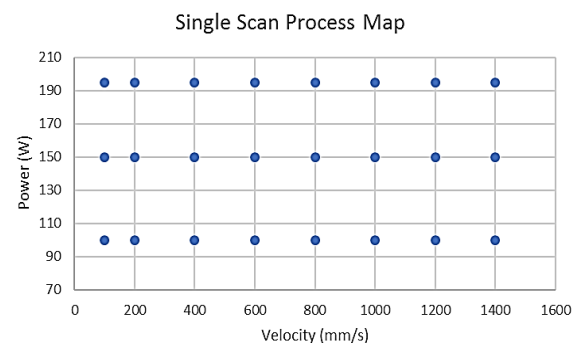


FIGURE 5. PV combinations for scan lines

Once printed, height maps of the single scans were obtained using a coherence scanning interferometer (CSI) and processed using a commercial software package. Each scan line was stitched with a 20x objective ($418 \mu\text{m}^2$ field of view (FOV)) with an overlap of 20 % between sites. After the data is leveled and the height data from the base plate removed, it can be seen in Figure 6A that the chevron pattern is barely visible in the unfiltered measurement. Even the larger spatial frequency chevrons are roughly an order of magnitude smaller than the scan line itself. Removing a best fit cylinder flattens the scan line, improving the visualization of the chevron pattern. The pattern can be further highlighted by applying appropriate Fourier filters. Figure 6B shows the scan line with a Fourier band-pass filter at a frequency of 20 per mm to 100 per mm. At this point, the large-scale chevron pattern is fully segmented from the underlying surface. However, adjusting the filter cutoffs to 100 per mm to 300 per mm can further bring out the finer scale features of this pattern as shown in Figure 6C.

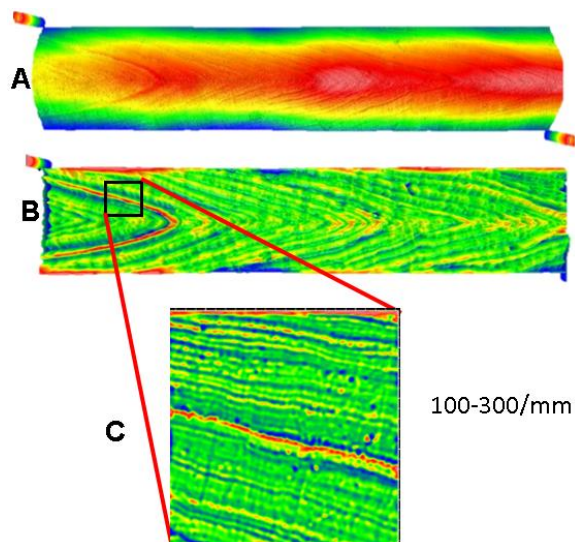


FIGURE 6. A) Unfiltered scanline. B) Scan line with cylinder removed and a Fourier bandpass filter from 20 per mm to 100 per mm. C) Filter cutoffs adjusted to 100 per mm to 300 per mm.

With chevrons isolated from the surface, areal autocorrelation was used to evaluate the angle of this heavily repeated pattern. The chevrons are measured where the scan track had reached steady state and are highly symmetric (Figure 6B). This allows for the left leaning legs of the chevron pattern (Figure 6C) to be analyzed, simplifying the analysis. ISO 25178 [14] defines three autocorrelation parameters: the fastest decay autocorrelation length (S_{al}), the texture aspect ratio (S_{tr}), and the texture direction (S_{td}). These parameters provide information not only on how directional the surface being analyzed is, but also the direction of the fastest and slowest decay of the autocorrelation length. The angle at which the major radius of the center lobe occurs gives the parameter S_{td} which coincides with the angle of the chevron pattern shown in Figure 7. Cooling length is calculated by taking half the width of the scan line divided by the tangent of the found chevron angle from the autocorrelation function.

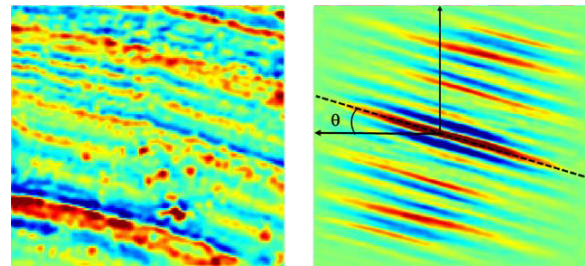


FIGURE 7. Chevron height map (Left). Autocorrelation of surface and S_{td} designated as θ (Right)

RESULTS AND DISCUSSION

From this measurement method, it is clear that the chevron pattern itself shows some variation in angle from the center of the scan line to the edges. It is likely that this is due to the legs of this pattern being slightly rounded. While this leads to some variation in angle in each scan line, this method has still proven viable in telling the differences between scan lines and approximating the cooling length of the melt pool ex situ. Figures 8 and 9 show the results from six runs of 24 scan lines and their comparison with modeling predictions for the scan track width and cooling length. Track width was measured ex-situ through microscope images taken over 1 mm of track. Images are taken at, nominally, the center of the track to avoid any edge effects. This measurement method is outlined by work conducted by Fox *et. al.* [15].

The model chosen for comparison is the Rosenthal solution [16]. The Rosenthal solution provides the analytical explanation to a moving heat source, originally developed to understand welding. Dykhuizen and Dobranich later adapted this model, applying it to laser based additive manufacturing processes [17, 18]. From Figure 8, one can see the experimental results of width measurement with error bars set to 1 standard deviation. Experimental width measurements match not only the predicted pattern, but also the approximate values modeled by the Rosenthal solution.

Cooling length measurements, shown in Figure 9 with error bars set to the largest deviation from the mean, appear to diverge from the model's predictions. This, however, was expected as the Rosenthal solution is a fairly simplified model and does not take into account some of the physical processes occurring during the build. Among those not considered is the creation of voids in the wake of the melt pool due to processing

conditions with high energy density, referred to as keyholing. Excluding the region where keyholing is expected (all power cases for the 100 mm/s and 200 mm/s cases), a linear pattern is apparent. Though not predicted by the model, some of these linear trends have a slight negative slope. The decrease in cooling length as velocity increases for a given power is feasible as the energy imparted into the surface is decreased with faster scan speeds when all else is held constant. Results of this very slight cooling length decrease as velocity increases coincide closely with results shown by Heigel and Lane's in-situ thermographic measurements of melt pool lengths, however in both cases more results are needed [19]. Model results for cooling length could also be improved by moving toward higher fidelity finite element simulations as well as incorporating more physics into the process [20].

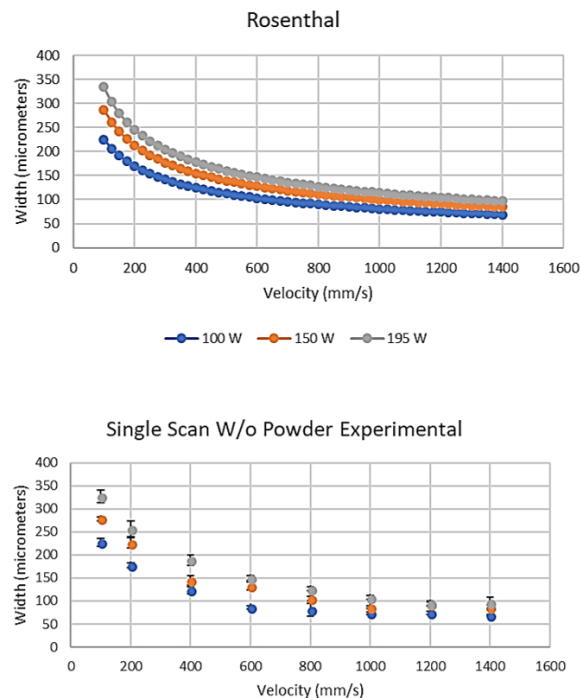


FIGURE 8. Experimental melt pool width comparison with the Rosenthal solution data (error bars set to one standard deviation).

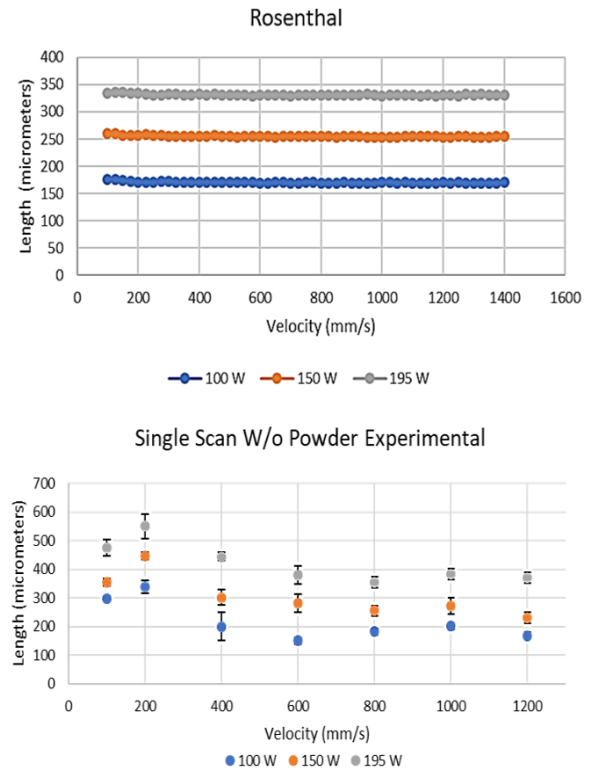


FIGURE 9. Experimental cooling length comparison with the Rosenthal solution data (error bars set to largest deviation seen).

FUTURE WORK

This work will be expanded in two major directions. The scan lines measured in this work will be sectioned and undergo microstructural analysis to relate microstructure to the length-to-depth ratio of the melt pool. This method will also be applied to single scan lines with powder as well as multiple adjacent scan tracks with and without powder to understand how this analysis method will progress when applied to building full sized parts.

REFERENCES

- [1] Mumtaz KA, Hopkinson N. Selective Laser Melting of thin wall parts using pulse shaping. *Journal of Materials Processing Technology* 2010;210:279-287. doi:10.1016/j.jmatprotec.2009.09.011
- [2] Liu X, Chu PK, Ding C. Surface modification of titanium, titanium alloys, and related materials for biomedical applications. *Materials Science and Engineering: R: Reports* 2004;47:49-121. doi:10.1016/j.mser.2004.11.001.
- [3] Lane BM, Moylan SP, Whitenton EP. PostProcess Machining of Additive

- Manufactured Stainless Steel. Proceedings of the 2015 ASPE Spring Topical Meeting: Achieving Precision Tolerances in Additive
- [4] Yasa E, Kruth J-P, Deckers J. Manufacturing by combining Selective Laser Melting and Selective Laser Erosion/laser re-melting. *CIRP Annals - Manufacturing Technology* 2011;60:263–6. doi:10.1016/j.cirp.2011.03.063.
 - [5] Measurement Science Roadmap for Metal Based Additive Manufacturing, Gaithersburg, MD: NIST; 2012.
 - [6] Z. Reese *et.al.* Observations on the surface morphology of laser powder bed fusion metal surfaces. *Met and Props* 2017, June 2017, Gothenburg, Sweden. Unpublished conference paper, 2017.
 - [7] Fox, Jason C., Shawn P. Moylan, and Brandon M. Lane. "PRELIMINARY STUDY TOWARD SURFACE TEXTURE AS A PROCESS SIGNATURE IN LASER POWDER BED FUSION ADDITIVE MANUFACTURING." *2016 Summer Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing*. 2016.
 - [8] Fox JC, Moylan SP, Lane BM. Effect of process parameters on the surface roughness of overhanging structures in laser powder bed fusion additive manufacturing. *Procedia CIRP*, Charlotte, NC: 2016. doi:10.1016/j.procir.2016.02.347
 - [9] Senin, Nicola, and Richard K. Leach. "Information-rich surface metrology." *Procedia CIRP* (2018).
 - [10] Gockel, Joy, and Jack Beuth. "Understanding Ti-6Al-4V microstructure control in additive manufacturing via process maps." *Solid Freeform Fabrication Proceedings*, Austin, TX, Aug (2013): 12-14.
 - [11] Keller, Trevor, et al. "Application of finite element, phase-field, and calphad-based methods to additive manufacturing of Ni-based superalloys." *Acta Materialia* (2017).
 - [12] Ghosh, Supriyo, et al. "On the primary spacing and microsegregation of cellular dendrites in laser deposited Ni–Nb alloys." *Modell. Simul. Mater. Sci. Eng* (2017).
 - [13] Gockel, Joy, Jack Beuth, and Karen Taminger. "Integrated control of solidification microstructure and melt pool dimensions in electron beam wire feed additive manufacturing of Ti-6Al 4V." *Additive Manufacturing* 1 (2014): 119-126.
 - [14] ISO 25178-2 (2012) – Surface texture: Areal - Terms, definitions, and surface texture parameters
 - [15] Fox JC, Lane BM, Yeung H, "Measurement of process dynamics through coaxially aligned high speed near-infrared imaging in laser powder bed fusion additive manufacturing", *Proc. SPIE 10214, Thermosense: Thermal Infrared Applications XXXIX*, 1021407 (5 May 2017); doi: 10.1117/12.2263863
 - [16] D. Rosenthal: *Trans. ASME*, 1946, vol. 68, pp. 849–66.
 - [17] R. Dykhuizen and D. Dobranich: "Analytical Thermal Models for the LENS Process," Sandia National Laboratories Internal Report, 1998.
 - [18] R. Dykhuizen and D. Dobranich: "Cooling Rates in the LENS Process," Sandia National Laboratories Internal Report, 1998.
 - [19] Heigel, Jarred C., et al. "Measurement of the melt pool length during single scan tracks in a commercial laser powder bed fusion process." *Proc. MSEC, Los Angeles, CA* (2017): 575-591.
 - [20] Francois, Marianne M., et al. "Modeling of additive manufacturing processes for metals: Challenges and opportunities." *Current Opinion in Solid State and Materials Science* 21.LA-UR-16-24513 (2017).

SIMULATION FOR XCT AND CMM MEASUREMENTS OF ADDITIVELY MANUFACTURED SURFACES

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INTRODUCTION

High level surface roughness of additively manufactured (AM) parts pose challenges to the applicability of tactile and X-ray computed tomography (XCT) techniques.

Tactile measurement techniques, e.g. coordinate measurement machines (CMMs) coupled with tactile probes, are traditionally considered to have a good level of accuracy and traceability. However, a tactile measurement can be significantly affected by the interaction of the stylus tip and the surface texture. Due to the finite size of stylus tip, it has a limited penetration into deep or narrow valleys and thus the true surface is never detected. This inability to trace the true profile of the surface is known as the mechanical filtering effect [1, 2].

XCT does not have the limitation of mechanical filtering effect. If sufficiently small voxel size compared to surface texture and sufficiently small focus spot size are available for XCT measurements, e.g. nano XCT systems, XCT can theoretically measure short wavelength components of surface texture, allowing the virtual probing of sharp valleys on surfaces [3]. However, in reality XCT systems, due to their measurement principles and hardware limitations, generates a low-pass filtering effect, where both surface peaks and valleys are smoothed [4]. The averaging effect is caused by the partial volume effect (PVE) of the XCT system, which refers to the 3D image blurring/fuzziness introduced by the finite spatial resolution of the XCT imaging system and image sampling [5, 6].

Comparisons of CMM and XCT measurements of AM parts via physical experiments are widely available [3,7-9]. Nonetheless, simulation can provide supplementary insight on how a single

factor can influence measurement. Another advantage of using simulation is that it can provide ideal reference data to evaluate measurement errors, which is particularly useful for AM surface measurements. This paper is a follow-on work of our previous publication [10], aiming to simulate XCT and CMM measurements of AM surfaces and investigate their measurement uncertainties.

SIMULATION PROCEDURES

XCT Scanning Simulation

The XCT simulation procedure is given in *FIGURE 1*.

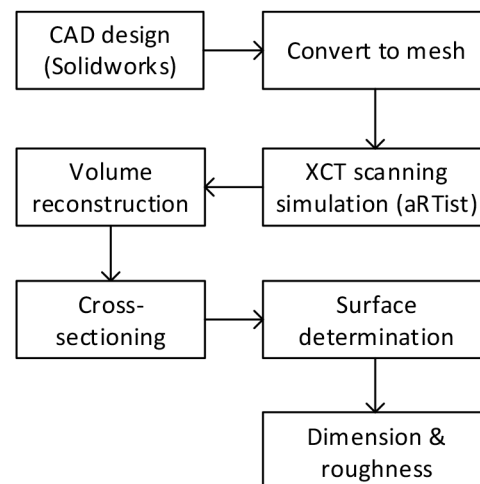


FIGURE 1. Simulation procedure for XCT measurements.

A cylinder component with “rough” surface is designed using Solidworks [11] and exported as a triangular mesh in STL (stereolithography) format. The STL file is then imported into the XCT simulation software aRTist [12], which performs simulated XCT scanning. The parameters of simulation software are optimised to mimic real scan setting, including a cone

beam X-ray with reflection tungsten target, at 100 kV and a flat panel detector with $0.2 \mu\text{m} \times 0.2 \mu\text{m}$ pixels, 2000×2000 data points. A point source X-ray source is considered and a 5×5 multiple sampling is considered in the detector. In the simulation, the sample was rotated 360° and 3142 projection images were taken. The simulation is illustrated in Figure 2. The simulation approach can eliminate the influence of those factors associated to physical XCT scans, e.g. scattering, thermal errors, and allows only the effect of partial volume effect to be investigated. The generated projection images are then reconstructed into the volumetric model and the cross-section slice images are taken at different heights. These section images are analysed by the developed 2D local searching algorithms to find out the surface boundary of the cylinder. Finally, the dimension and roughness of the extracted cylinder circumference profile are examined.

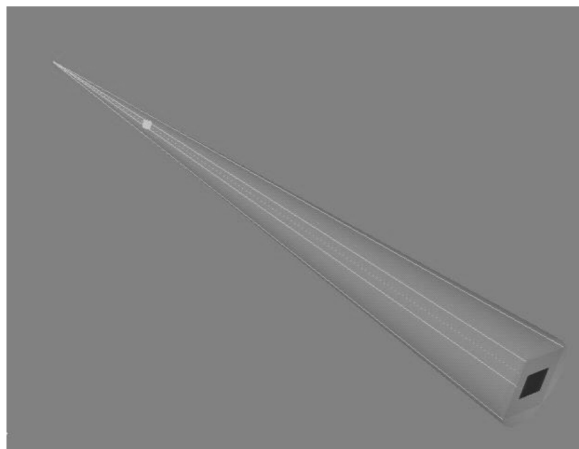


FIGURE 2. XCT simulation using aRTist

CMM Scanning Simulation

The CMM scanning simulation procedure is illustrated in FIGURE 3. The CMM scanning is simulated on the 2D cylinder cross-section profile directly. The morphological method [10] is used to simulate the effect of diameter of tactile probe during physical scans, including three tactile spherical probe tips with tip diameters 3 mm, 4 mm and 5 mm respectively. Due to physical size of tips, CMM is only used to measure dimensions, i.e. the cylinder radius.

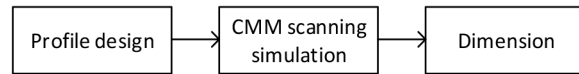


FIGURE 3. Simulation procedure for CMM measurements.

Cylinder CAD for XCT Simulation

A cylinder CAD model is constructed, comprising an ideal cylinder and a sinusoidal wave superimposed on the cylinder's lateral surface to simulate rough AM surface texture. See FIGURE 4. The cylinder's cross-section profile is specified by the parametric equation:

$$\begin{cases} x = (7 + 0.05 \sin(200t)) \cdot \sin(t) \\ y = (7 + 0.05 \sin(200t)) \cdot \cos(t) \end{cases} \quad t \in [0, 2\pi] \quad (1)$$

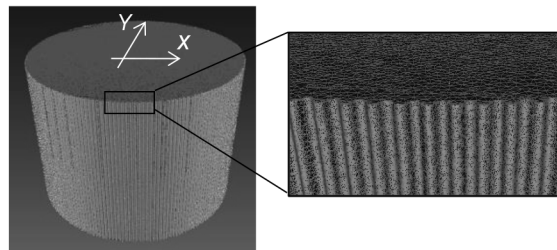


FIGURE 4. Cylinder model with rough texture.

Cross-section Profile For CMM Simulation

A cross-section cylinder profile is generated by following the same equation to ensure the diameters resulted from the CMM simulation can be compared to that of XCT. See FIGURE 5.

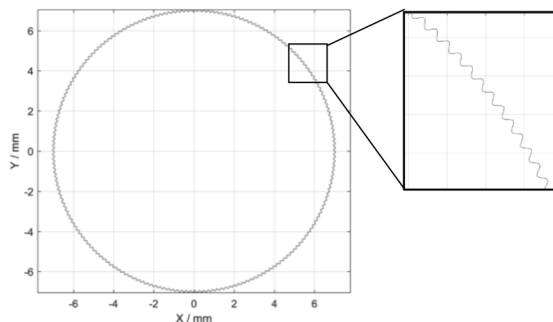


FIGURE 5. Cross-section cylinder profile.

SURFACE EXTRACTION

Surface Determination of XCT Measurements

The global thresholding method uses the information on the grey value histogram to select a particular value as representation for the measurand's edge [13]. For example, the ISO 50 method takes the average of the material peak grey value and the background peak grey value. This threshold value is then used to

differentiate the material voxels from the background voxels. Marching cube algorithm is widely used to determine the points from edge voxels [14]. In this paper, surface boundary is determined on the 2D cross-section images, and thus the marching square (2D version of the marching cube) is used.

The ISO 50 method is found not be able to determine an accurate surface boundary. It is suggested that the local thresholding algorithms which search local maximum gradients are more accurate [15-17]. In this study, a local searching algorithm is implemented to generate the surface contours from 2D cross-section images of a 3D object.

The developed local searching algorithm takes the ISO 50 contour as the initial boundary, based on which it searches for the maximum gradient along contour normals. This is based on the assumption that the surface boundary locates at the positions where the largest gradients occur. *FIGURE 6* shows a portion of the ISO 50 contour and the resulted normal vectors. A spline filter can be applied to smooth the initial contour and thus generate more stable contour normals.

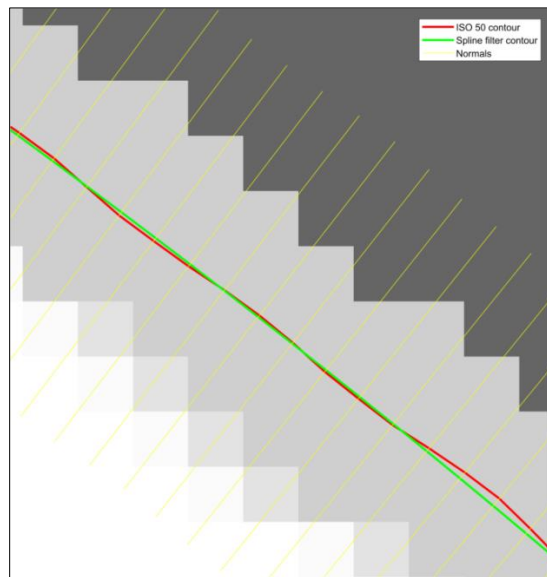


FIGURE 6. Partial ISO 50 contour, contour smoothed by the Spline filter, and normal vectors (Pixels of this cross-section image are equalised for a better visual contrast).

A profile is extracted by the grey values of pixels where the search path passes through within the specified distance, e.g. 4 pixels on both sides of

the contour point along the normal vector. Bicubic interpolation [18] is used to improve the accuracy of locating the maximum gradient position (at subpixel level). *FIGURE 7* illustrates such an grey value profile, where the interpolation distance is set to the tenth of the pixel size.

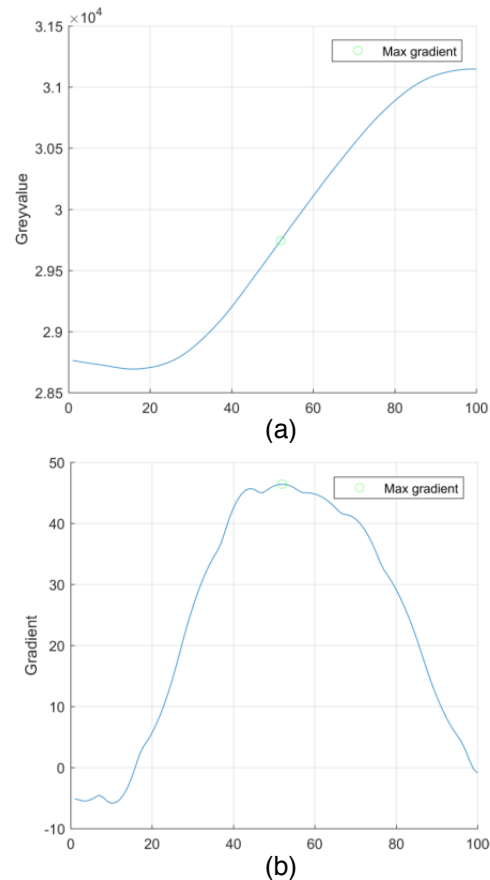


FIGURE 7. Detection of the maximum gradient position: (a) the grey value profile along the search path; (b) the resulted gradient profile.

In case that measurement noises are presented, appropriate filters, e.g. the spline filter, can be applied to denoise the grey value profile in order to find the more reliable maximum gradient location.

FIGURE 8 illustrates the cylinder circumference contours generated by the ISO 50 and the local gradient searching method. Visually, the contour produced by the local searching method is the better revealing the designed sinusoidal wave, while the ISO 50 contour is smoother and is unable to present the wave. In addition, the local searching contour resides towards the material

side of the cylinder in comparison to the ISO 50 method.

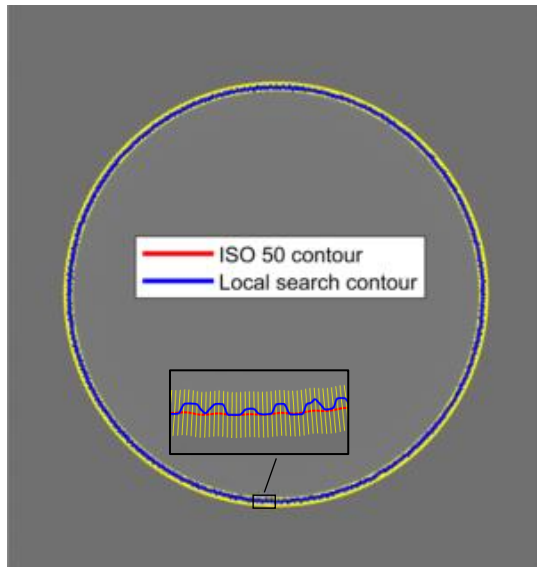


FIGURE 8. Surface boundaries detected by the ISO 50 method and the local adaptive method.

The local searching algorithm can be further optimised by customising the searching distance, the increment distance and the maximum iteration number, whenever required.

Morphological Method for CMM Measurement Simulation

The morphological method was employed to numerically simulate probing of physical surfaces using CMM [10]. This method places an infinite number of identical disks in contact with the surface profile from above along all the profile and taking the upper boundary of the disks (i.e. the closing envelope). See FIGURE 9. This mechanism is consistent with tactile probing.

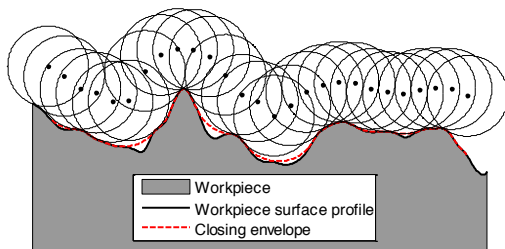


Figure 9. The closing envelope of a surface profile by a disk.

The adopted algorithm is based on the Alpha shape theory [19, 20]. It extracts the boundary facets of the alpha shape from the Delaunay

triangulation. See FIGURE 10 for an example of computing the closing envelope of a cylinder circumference profile.

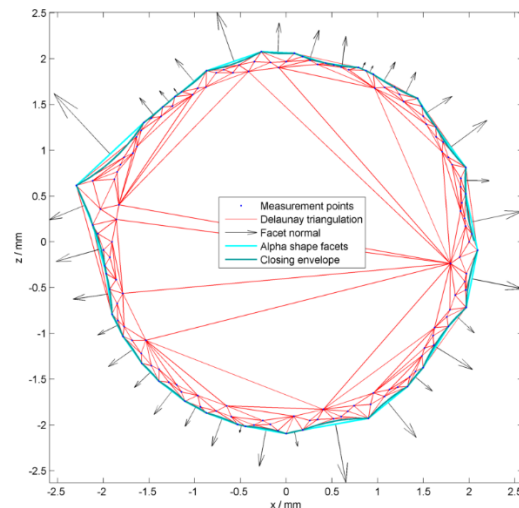


Figure 10. The morphological filtering on the cylinder circumference profile based on Alpha shape algorithm.

Three disk probes with diameters of 3 mm, 4 mm and 5 mm are simulated. FIGURE 11 illustrates three corresponding morphological closing envelopes. It should be noted that both the profile and envelopes are suppressed by 6.5 mm for better visualisation.

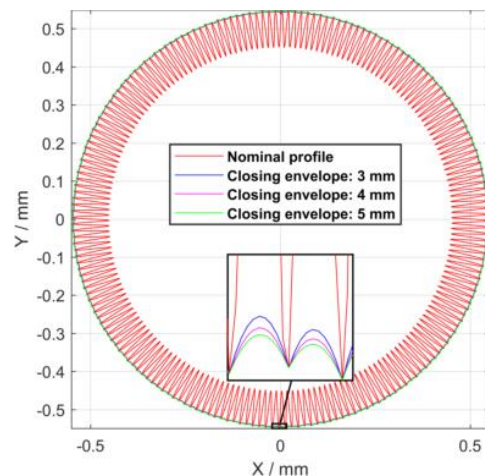


FIGURE 11. Closing envelopes of 3 mm, 4 mm and 5 mm disk probes.

SIMULATION RESULTS

XCT and CMM simulation results are listed in:TABLE 1-3. In XCT simulation, both dimensional and roughness results show that the local searching algorithm is more accurate than the ISO 50 method. Simulation also

indicates that taking the simulated probe tip sizes (3 mm, 4 mm and 5 mm) and also the XCT voxel sizes (10 μm , 30 μm and 50 μm), the dimensional deviations caused by the partial volume effect of XCT are smaller than the mechanical filtering effect of CMM, particularly when the local adaptive algorithm is applied. This fact therefore implies that in case of rough texture is presented in component's surface, e.g. AM surface, the deviations caused by the mechanical filtering effect of CMM tactile probe are significant for high accuracy dimensional measurements. Larger probe diameters produce a greater offset from the nominal surface profile in cylinder diameters. This fact should be taken into consideration when tactile CMM is used for dimensional measurements of AM components.

TABLE 1. Cylinder radii estimated from XCT simulation.

Voxel size (μm)	Nominal cylinder radius: 7 mm			
	ISO 50 (mm)	Dev (μm)	Local adaptive (mm)	Dev (μm)
10	7.0221	22.1	7.0156	15.6
30	7.0318	31.8	7.0092	9.2
50	7.0313	31.3	7.0086	8.6

TABLE 2. Cylinder roughness (R_a) generated from XCT simulation (No filtration applied).

Voxel size (μm)	Nominal Roughness: R_a 31.8 μm			
	ISO 50 (μm)	Dev (μm)	Local adaptive (μm)	Dev (μm)
10	15.9	-15.9	20.7	-11.4
30	4.4	-27.4	11.3	-20.5
50	4.7	-27.1	8.2	-23.6

TABLE 3. Cylinder radii estimated from CMM simulation.

Tip diameter (mm)	Nominal cylinder radius: 7 mm	
	Cylinder radius (mm)	Dev (μm)
3	7.0459	45.9
4	7.0465	46.5
5	7.0469	46.9

CONCLUSION AND FUTURE WORK

Simulation methods are proposed to compare XCT and CMM measurements for AM surfaces. The local searching method and the morphological method are developed to determine surface boundaries of the designed cylinder for XCT and CMM measurement respectively. The simulation results show rough surface texture has more impact on CMM measurement in comparison to XCT measurement. The results also indicate the local

searching method is more accurate than the ISO 50 method for XCT measurement.

Future work includes further optimisation of simulated XCT scanning and investigation of the impact of voxel sizes on dimensional and surface measurement.

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REFERENCES

- [1] Whitehouse D Surfaces and their measurement, Hermes Penton Science, 2002.
- [2] Thomas T R Rough Surfaces, London, UK: Imperial College Press, 1999.
- [3] Aloisi V, Carmignato S Influence of surface roughness on x-ray computed tomography dimensional measurements of additive manufactured parts, Case Studies in Nondestructive Testing and Evaluation, 2016; 6: 104-110.
- [4] Kruth J P, Bartscher M, Carmignato S, Schmitt R, De Chiffre L, Weckenmann A Computed Tomography for Dimensional Metrology, CIRP Ann. 2011; 60: 821-842.
- [5] Soret M, Bacharach S L, Buvat I Partial-volume effect in PET tumor imaging, Journal of Nuclear Medicine 2007; 48: 932-45.
- [6] Volume Graphics, VGStudio Max 2.0 Reference Manual 2.0, www.volumegraphics.com
- [7] Brown S, Sun W, McCarthy M B, Woolliams P Assessment of dimensional measurement tools to measure additively manufactured metallic parts, Proceedings of ASPE Summer Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing 2016; 200-205.
- [8] Schmitt R, Niggemann C Uncertainty in measurement for x-ray-computed tomography using calibrated work pieces,

- Measurement Science and Technology; 2010; 21: 054008.
- [9] Carmignato S, Aloisi V, Medeossib F, Zaninia F, Savio E Influence of surface roughness on computed tomography dimensional measurements, CIRP Annals 2017; 66: 499-502
- [10] Lou S, Brown S B, Sun W, Zeng W, Abdul-Rahman H S, Jiang X, Scott P J 2017 Use of morphological method to investigate the influence of surface texture on dimensional measurement of additively manufactured parts, EUSPEN Special Interest Group Meeting: Dimensional Accuracy & Surface Finish in Additive Manufacturing, KU Leuven, Belgium.
- [11] Solidworks, <http://www.solidworks.com/>.
- [12] BAM, aRTist, <http://www.artist.bam.de/>.
- [13] Tan Y, Kiekens K, Kruth J-P, Voet A, Dewulf W Material Dependent Thresholding for Dimensional X-ray Computed Tomography, International Symposm on Digital Industrial Radiology and Computed Tomography, Berlin, June 20–22, 2011.
- [14] Lorensen W E, Cline H E Marching cubes: A high resolution 3d surface construction algorithm. ACM Computer Graphics. 1987; 21(4): 163-169.
- [15] Borges de Oliveira F, Stolfi A, Bartscher M, De Chiffre L, Neuschaefer-Rube U Experimental investigation of surface determination process on multi-material components for dimensional computed tomography, Case Studies in Nondestructive Testing and Evaluation Part B, 2016; 6: 93-103.
- [16] Lifton J J, Malcolm A A, McBride J W On the uncertainty of surface determination in X-ray computed tomography for dimensional metrology, Measurement Science and Technology, 2015: 26 035003 .
- [17] Reinhart C Industrial CT & Precision, Volume Graphics GmbH, Heidelberg, Germany, 2011.
- [18] Keys R Cubic convolution interpolation for digital image processing. IEEE Transactions on Acoustics, Speech, and Signal Processing. 1981; 29 (6): 1153-1160.
- [19] Lou S, Jiang X, Scott P J Geometric computation theory for morphological filtering on freeform surfaces, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences A 2013; 469: 20130150.
- [20] Lou S, Jiang X, Scott P J Morphological filters for functional assessment of roundness profiles, Measurement Science and Technology, 2014; 6: 065005.

COMPLEMENTARY USE OF OPTICAL METROLOGY AND X-RAY COMPUTED TOMOGRAPHY FOR SURFACE FINISH AND DEFECT DETECTION IN LASER POWDER BED FUSION ADDITIVE MANUFACTURING

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INTRODUCTION

The development of additive manufacturing (AM) has allowed for production of high-value and complex parts that reduce time-to-market and cost to manufacture [1]. A key benefit of the AM process is the capability to create lattice structures and highly complex, topology optimized parts that reduce weight. Despite this advantage, a limiting factor affecting widespread adoption of AM is the sometimes less desirable as-built surface topography of finished parts compared to those made using traditional manufacturing techniques. As part complexity increases, the ability to alter the surfaces through a secondary operation (i.e., machining or polishing), either in situ or ex situ, decreases [2]. Thus, improvements in the as-built surface texture and understanding its relationship to part quality has been cited as a key need [1,3].

In addition to a stronger understanding of the as-built surface texture of AM parts, development of non-destructive evaluation (NDE) techniques such as x-ray computed tomography (XCT) for surface texture measurement is needed. Traditional surface metrology equipment often requires line of sight or adequate clearance to contact the surface with a stylus, which can be difficult to achieve given the highly complex AM geometries [4]. Townsend et al. presented a methodology to extract areal surface texture from XCT data and compared it with a focus variation (FV) microscopy measurements [5]. Thompson et al. also showed a comparison and alignment of confocal microscopy, coherent scanning

interferometry, and FV to XCT data. XCT data in this work was first rotated to align the surface normal to the z-axis via principal component analysis and then translated via commercially available software. The work also suggested the integration of results to improve understanding of complex surface topography measurement [6,7].

The purpose of this research is to investigate the complementary use of optical metrology and XCT for inspection of parts built through laser powder bed fusion (L-PBF) AM, with the primary focus being the benefit that the volumetric XCT data can provide when aligned with the data from conventional surface metrology equipment. Samples made from 17-4 stainless steel (17-4SS) and nickel super alloy 625 (IN625) are measured using a laser confocal (LC) microscope and XCT system. Defects, which include reentrant features on the surface and near surface pores, are identified and located from the XCT data using methodologies described by Fox et al. [8]. The data from the XCT and laser confocal (LC) systems is then aligned using an iterative closest point (ICP) algorithm. This alignment allows for identification of locations in the LC data close to near-surface defects and provides more context for numerical analysis.

METHODOLOGY

Optical Measurements

Surface height data was acquired with a Zeiss LSM 800 LC system. All measurements were performed with a 10x objective and 0.5x tube lens or a 20x objective lens. These settings create

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lateral resolutions of 1.25 μm and 0.31 μm , respectively. Measurements were processed with Digital Surf's ConfoMap software to remove outliers and level the surfaces. No other filtering was applied to the data.

XCT Measurements

XCT scans were acquired with North Star Imaging (NSI) CXMM 50 metrological CT system. The system is equipped with a 225 kV source including a tungsten target, a rotary stage, and a 127 $\mu\text{m}/\text{pixel}$ flat panel detector (FIGURE 1). The voxel size of the XCT data was 10.9 μm . A typical filtered backprojection algorithm supplied by the vendor was used to reconstruct the dataset [9]. XCT acquisition parameters are shown in TABLE 1, and the methodology for selection of those parameters are detailed in Fox et al [8].

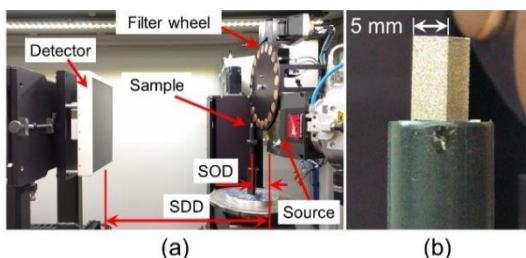


FIGURE 1. (a) XCT system setup, and (b) an example image of the sample.

TABLE 1. XCT acquisition parameters

Parameter	Value
Voltage	160 kV
Current	80 μA
Exposure time	2 s
Filter material/thickness	Cu/4 mm
Number of projection	1000
Source-to-detector distance (SDD)	492.76 mm
Source-to-object distance (SOD)	42.29 mm
Voxel size	10.9 μm x 10.9 μm x 10.9 μm

Experiment Samples

Parts for the analysis were built on the EOS M270 system at the National Institute of Standards and Technology (NIST). Three parts were built for this analysis: two using the commercially available EOS StainlessSteel GP1 (corresponds to US classification 17-4SS [10]) and one EOS NickelAlloy IN625 (corresponds to classification unified numbering system UNS N06625 [11]). It should be noted that the material used for the build was powder reclaimed from prior builds

using an 80 μm sieve. It is assumed that the condition of the powder can have a large effect on the surface quality of parts being built and analysis of the powder is currently underway.

For the two parts built using the 17-4SS, the first was built entirely with the default parameters defined by the manufacturer, and will be referred to as "sample 60." The second was built with a laser power of 195 W and laser scan speed of 700 mm/s for the contour passes only (outermost portion of the part) with the rest of the parameters set to the default defined by the manufacturer. This will be referred to as "sample 195". This high power contour setting was chosen because prior work by the authors had shown that these settings create a greater variety of surface features [4,12]. The part built using the IN625 was built with the default parameters defined by the manufacturer and will be referred to as "sample 625." Samples built for the analysis are shown in FIGURE 2.

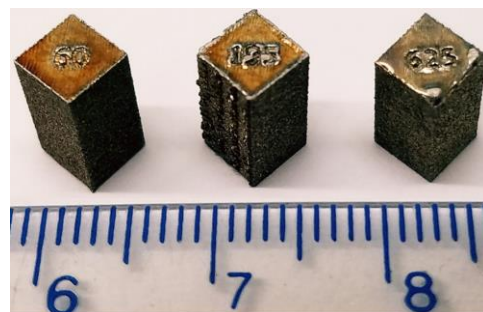


FIGURE 2. Sample 60 (left), sample 195 (center), and sample 625 (right). Scale is in cm.

The samples were built with the same orientation in the build chamber relative to the recoater blade. Surfaces of the samples will be referred to as follows: the top surface is parallel with the build plane and contains the part labels "60," "195," and "625," seen in FIGURE 2. Side surfaces will be referred to using primary intercardinal directions when looking down at the label on the top surfaces. For example, in FIGURE 2, the southeast (SE) and southwest (SW) surfaces of each part can be seen and the northeast (NE) and northwest (NW) surfaces cannot be seen.

RESULTS

Analysis of Optical Metrology Data

Height measurements were taken from the surfaces of the samples using a laser confocal microscope. The sample is aligned in the instrument such that the positive y-axis of the microscope is parallel to the build direction, the intersection of the top surface and left edge of the

sample is at (0,0). Each surface was scanned over a 5 x 5 stitch using a 10x objective and 0.5x tube lens to create a 5.89 mm x 5.89 mm view of the surface with 1.25 μm point spacing. Additionally, each surface was scanned over a 3 x 3 stitch using a 20x objective and 1.0x tube lens to create an 895 μm x 895 μm view of the surface with 0.31 μm point spacing. The scan center was positioned at (2.5,-3) mm.

Analysis of XCT Data

The reconstructed XCT data were imported into VGStudioMAX 3.0 software and the 3-2-1 registration technique available in the software was used to align the orthogonal faces to the same coordinate system and minimize part-to-part variation during the analysis [13]. Then, a stack of images was exported such that the cross-sectional image shows both SW and NE edges of the sample. In addition to the 10.9 μm per voxel resolution, a sub-voxel interpolation to 2.5 μm per voxel was performed through commercially available software and was used to create images for analysis at a higher resolution [14]. From these images, a 2D array of surface heights can be created using the methods described in Fox et al. [8].

Data Alignment

To align the data from various sources, height maps were converted to point clouds and registered using an ICP algorithm, available in the commercially available MATLAB software package. Alignment was performed in multiple steps. For alignment of the 20x LC data and 10x LC data, an initial crop of the 10x LC data is performed to reduce the computational burden of the alignment and limit the search area to the general region where the 20x LC measurement was performed (2.5 mm to the right and 3 mm down from the upper left corner of the surface). From this point, all alignments were completed in two steps. In the first step, the lowest 70 % of points were ignored and the two surfaces are roughly aligned using the ICP algorithm on the highest 30 % of points on the surface. In the second step, the translation and rotation determined in the first step is used as the starting point for the ICP algorithm on the full set of surface points. The alignment was performed using these two steps because even a minor error in selection of a fiducial (on the order of tens of micrometers) can lead to errors in alignment on the order of millimeters in the x and y directions with the ICP algorithm. Aligned sections from the various data sources can be seen in FIGURE 3.

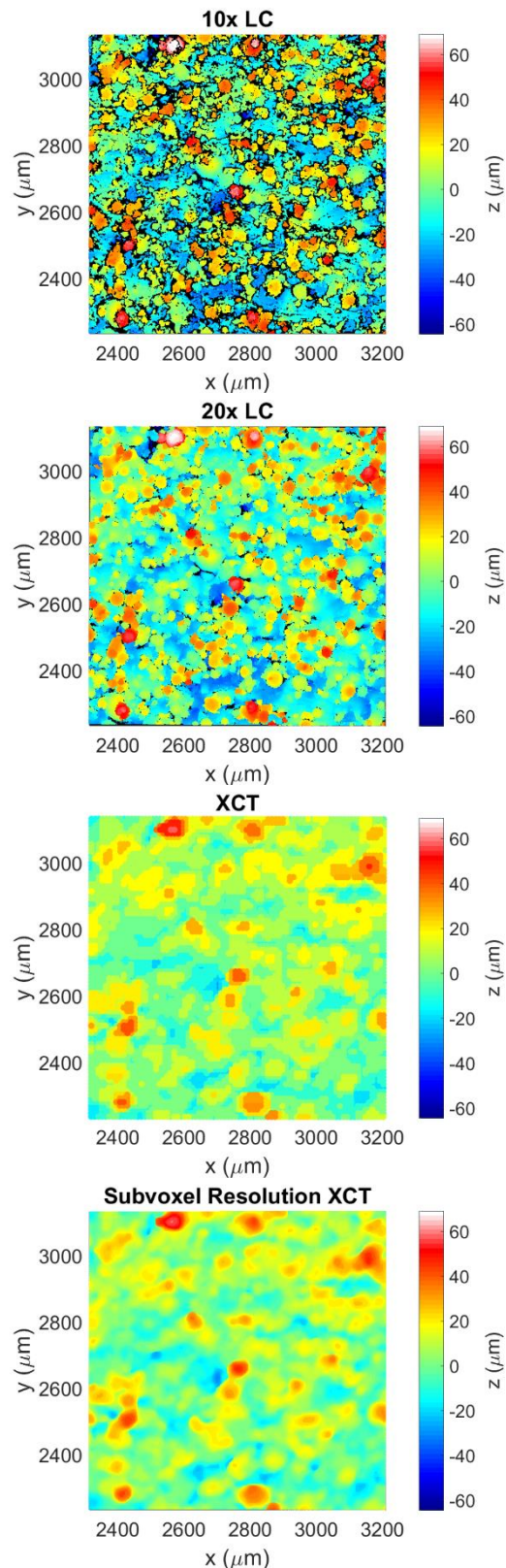


FIGURE 3. Aligned data maps from various sources.

Qualitatively, this method provides good alignment between the various sources. To analyze the quality of the alignment quantitatively, signed distance maps and distributions can be seen in FIGURE 4 through FIGURE 6. Additionally, the signed distances are used to determine the root mean square error (RMSE) between two aligned surfaces. It should be noted that while sub-voxel interpolation of the XCT data to 2.5 μm per voxel is available in the commercial software, it did not exhibit a significant difference in the identification of the surface from the original 10.9 μm per voxel data. This can be seen when comparing FIGURE 5 and FIGURE 6.

Identification of Defects

Images of the surface were taken via scanning electron microscope (SEM) for qualitative comparison. FIGURE 7 shows an example image from the SW surface of sample 60. The image shows a 1 mm x 1 mm area of the surface that encompasses the area previously scanned with the laser confocal microscope using the 20x objective.

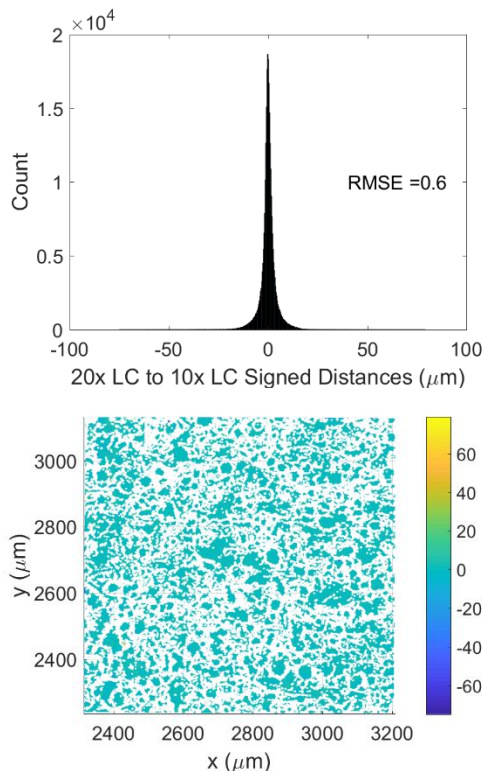


FIGURE 4. Signed distances distribution and map for alignment of the 10x LC and 20x LC data.

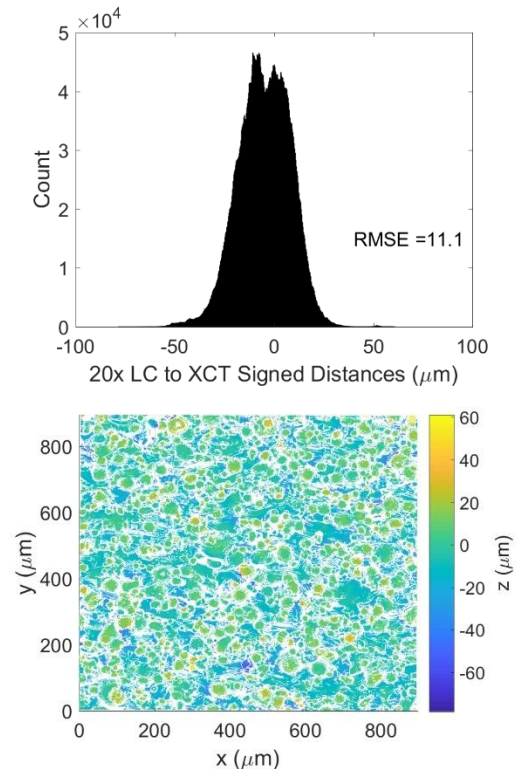


FIGURE 5. Signed distances distribution and map for alignment of the 20x LC and XCT data.

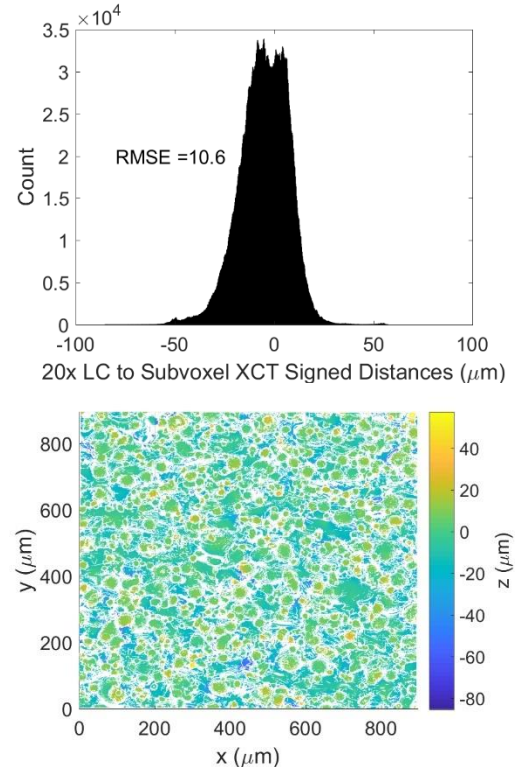


FIGURE 6. Signed distances distribution and map for alignment of the 20x LC and Sub-Voxel XCT data.

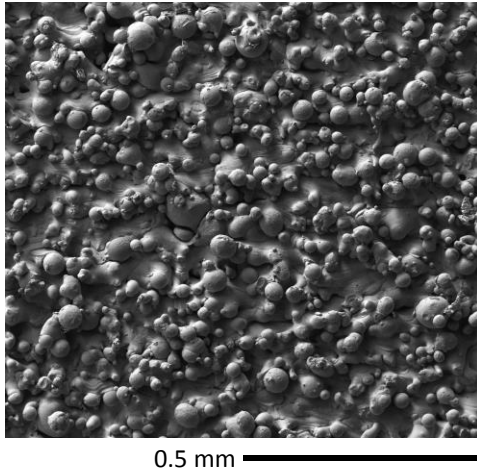


FIGURE 7. SEM image of the SW surface of sample 60.

While the current resolution of the XCT data is limited, it has the distinct advantage of being able to detect pores and undercuts on and near the surface. The method described in Fox et al. [8] was used to determine undercuts on the surface and sub-surface pores from the surface to approximately 275 μm below the surface. The resultant pore and undercut locations are presented in FIGURE 8.

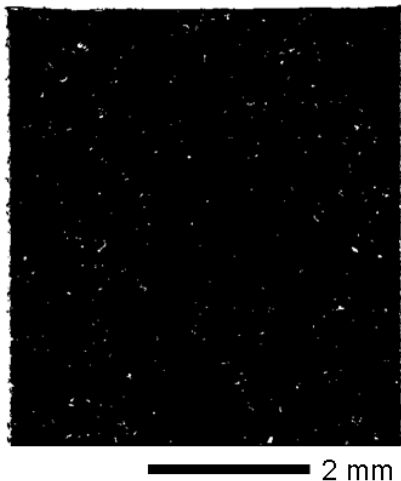


FIGURE 8. Location of near surface pores and undercuts on the SW surface of sample 60 identified from XCT data.

From the identification of pores and undercuts in FIGURE 8, surface data near these defects can be extracted from the previously aligned data sources. Defect locations are overlaid onto the 20x LC data in FIGURE 9. A closer view of the surface data near the rightmost defect location in FIGURE 9 (highlighted with a red box) is shown in FIGURE 10. While this methodology allows us

to align and identify regions where subsurface defects exist, it is still inconclusive whether trends in the surface data from the LC system can identify these defects. As such, further analysis of the surface data is ongoing.

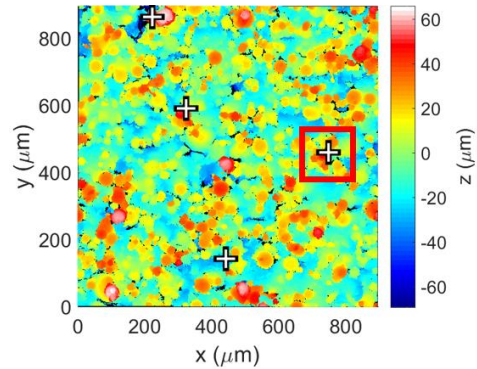


FIGURE 9. Surface data for the SW surface of sample 60, taken via 20x objective on the laser confocal system, with defect areas (pore and undercut locations) indicated by plus signs.

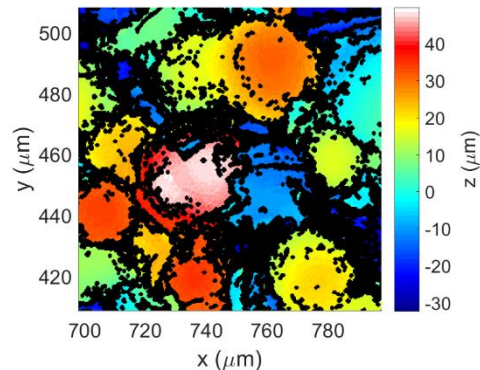


FIGURE 10. Surface data taken via 20x objective on the laser confocal microscope for the rightmost defect area (highlighted with a red box) in FIGURE 9.

CONCLUSIONS

In this work, IN625 and 17-4SS samples were built on a commercially available L-PBF system and analyzed via laser confocal microscope and XCT. The data were aligned using an ICP algorithm for complementary analysis. Pores and undercuts were identified using XCT data, which allowed for more stringent analysis of the surface near these features. However, at 10.9 μm per voxel the current resolution of XCT prevents strong quantitative analysis of the surface data from XCT or relevant comparison to the laser confocal microscope surface data. While quantitative analysis has been performed on XCT data with larger voxel sizes, it has utilized sub-voxel

interpolation. The current analysis has shown that sub-voxel interpolation provided little change in the determined surface, and greater benefit may be derived from proprietary surface determination algorithms in the commercially available software. This was not included in the current analysis.

Future work will include the classification of defects found in the data (i.e., subsurface pores vs undercuts on the surface), and identification of the depth of pores. Additionally, advanced pore detection techniques and image analysis, such as those presented in Kim et al. [15], and sectioning of the samples for comparison to the XCT and laser confocal microscope data are in progress. It is anticipated that this type of analysis will create avenues to get richer information from the surface data and add a potential methodology for feature based metrology.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] Measurement Science Roadmap for Metal-Based Additive Manufacturing. Gaithersburg, MD: NIST, US Department of Commerce; 2012.
- [2] Pyka G, Burakowski A, Kerckhofs G, Moesen M, Van Bael S, Schrooten J, et al. Surface modification of Ti6Al4V open porous structures produced by additive manufacturing. *Advanced Engineering Materials* 2012;14:363–70. doi:10.1002/adem.201100344.
- [3] America Makes & ANSI Additive Manufacturing Standardization Collaborative Standardization Roadmap for Additive Manufacturing, Public Draft v1.0. 2017.
- [4] Fox JC, Moylan S, Lane BM. Preliminary Study Toward Surface Texture as a Process Signature in Laser Powder Bed Fusion Additive Manufacturing. *Proceedings of the 2016 ASPE Summer Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing*, Raleigh, NC: 2016.
- [5] Townsend A, Pagani L, Scott P, Blunt L. Areal surface texture data extraction from X-ray computed tomography reconstructions of metal additively manufactured parts. *Precision Engineering* 2017;48:254–64. doi:10.1016/j.precisioneng.2016.12.008.
- [6] Thompson A, Körner L, Senin N, Lawes S, Maskery I, Leach R. Measurement of internal surfaces of additively manufactured parts by X-ray computed tomography. *7th Conference on Industrial Computed Tomography*, Leuven, Belgium: 2017.
- [7] Thompson A, Senin N, Giusca C, Leach R. Topography of selectively laser melted surfaces: A comparison of different measurement methods. *CIRP Annals - Manufacturing Technology* 2017. doi:10.1016/j.cirp.2017.04.075.
- [8] Fox JC, Kim FH, Reese ZC, Evans C. Investigation of complementary use of optical metrology and x-ray computed tomography for surface finish in laser powder bed fusion additive manufacturing, Leuven, Belgium: 2017, p. 132–6.
- [9] L.A. Feldkamp, L.C. Davis, J.W. Kress, Practical cone-beam algorithm, *J. Opt. Soc. Am. A* 1(6) 612-619. 1984.
- [10] Material data sheet - EOS StainlessSteel GP1 for EOSINT M270 2009. https://scrivito-public-cdn.s3-eu-west-1.amazonaws.com/eos/public/5f84f5d2c88ac900/05fb1582834a38c85ef6dd859733a230/EOS_StainlessSteel-GP1_en.pdf (accessed December 7, 2015).
- [11] Material Data Sheet - EOS NickelAlloy IN625 2011. http://ip-saas-eos-cms.s3.amazonaws.com/public/d1327facdc a0e32a/373a60ec4f5c891b7dbcdf572e37d3 b0/EOS_NickelAlloy_IN625_en.pdf (accessed June 13, 2017).
- [12] Fox JC, Moylan SP, Lane BM. Effect of Process Parameters on the Surface Roughness of Overhanging Structures in Laser Powder Bed Fusion Additive Manufacturing. *Procedia CIRP* 2016;45:131–4. doi:10.1016/j.procir.2016.02.347.
- [13] Volume Graphics GmbH, VGStudioMax 3.0.
- [14] Avizo 9.4, Thermo Fisher Scientific, Waltham, MA.
- [15] Kim FH, Moylan SP, Garboczi EJ, Slotwinski JA. Investigation of pore structure in cobalt chrome additively manufactured parts using X-ray computed tomography and three-dimensional image analysis. *Additive Manufacturing* 2017;17:23–38. doi:10.1016/j.addma.2017.06.011.

THE ROLE OF COMPUTED TOMOGRAPHY IN ADDITIVE MANUFACTURING

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INTRODUCTION

Additive manufacturing (AM) technologies—or 3D printing, as they are popularly known—show promise as a way to transform traditional production manufacturing because they can produce highly complex geometries and customized parts directly from the part design model without dedicated tooling. However, many questions about the structural integrity of 3D printed parts—tolerance limits, layer defects, residual stress, and material inclusions—remain unanswered because AM process parameters and disruptions during the material layering (generally in powder form) may induce a variety of dimensional deviations and internal flaws (e.g., cracks or voids) in the final product. These flaws might affect the performance of AM devices and create risks of potential failures, so the support of metrology and non-destructive testing (NDT) techniques for better assessment of AM parts is needed [1-5]. One of the challenges to perform the assessment of AM parts is that if such parts have internal features, these are generally inaccessible from the outside to vision-based inspection techniques for quality control, and while destructive methods can be used to extract measurements, dimensional information from the disassembled parts often show a discrepancy between the actual and measured dimensions of the parts. Based on current work that investigates how to overcome difficulties in AM metrology assessment, this paper describes some of the main issues associated with the measurement of AM parts and some future trends for the development of alternative techniques for measuring the complex forms of AM parts. Along with a brief discussion of limitations of traditional inspection technologies, such as coordinate measuring machines (CMMs) and optical-based systems, the particular case of X-ray computed tomography (CT) as a technology to support AM inspection and development is discussed. The benefits of X-ray CT for the assessment of the structural integrity of AM parts and deviations typically encountered in AM dimensional geometry when compared to reference/nominal geometry will be considered.

AM QUALIFICATION CHALLENGES

Due to its almost unlimited capability to produce highly complex geometries and customized parts directly from the part model, AM techniques have recently received significant attention as technologies that may have the potential to transform traditional manufacturing techniques into more cost-effective production processes. Since one of the main envisioned applications of AM is the creation of safety-critical components, such as those found in propulsion engine components and customized biomedical implants, the growth and development of AM technologies should be accompanied by quality control processes and inspection technologies. The need for established methods of AM qualification has been previously highlighted by several authors [1-7]. The rationale underpinning the call for AM qualification usually appeals to one or more of the following necessities: to understand the processing techniques and geometry impact on AM material properties; to understand and develop AM process optimization; to design methods of engineering that take advantage of the AM possibilities; to identify suitable parts for AM; to develop qualification standards for AM materials and quality control processes; and to develop in-situ measurement systems for inspecting AM processes. Whereas some researchers may stress the importance of raw material control and identifying the key variables impacting the manufacturing, others tend to accentuate a qualification approach that focuses on inspecting finished AM parts by combining the existing knowledge of qualification methods for conventional manufacturing processes. In reality, these approaches are related and connected because the impact of product geometry on the material microstructure is an inherent characteristic of the AM processes, which in turn directly affects the final product. However, the qualification of finished AM parts is challenging because such parts can be complex in form (e.g. freeform-shaped parts). They typically have a high surface roughness, and they may also have internal geometry with interconnected structures and channels. As

such, they can potentially contain voids and inclusions (such as unmelted particles or powder residues) inside their volume. These challenges make it difficult for conventional NDT techniques—such as ultrasonic, infrared, eddy current, radiographic inspection, and light-based technologies—to achieve comprehensive inspections on the quality of AM parts. But X-ray CT is an alternative technique that proves useful for examining parts of complex internal geometry. Although it still has limitations related to resolution, sensitivity, and speed, industrial CT equipment continues to develop and improve technologically. As a result, X-ray CT has been more successful in addressing some of the quality inspection needs for the AM industry and seems to be increasingly used as a tool for qualifying AM parts.

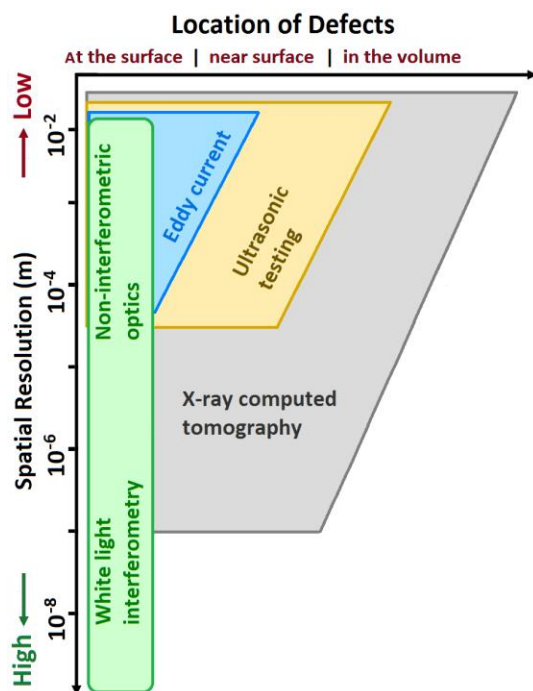


FIGURE 1. Comparison of some relevant NDT techniques according to detectable defect location and their achievable spatial resolution. Adapted from [8].

In Figure 1, there is a comparison of NDT techniques typically used for defect detection in AM parts and dimensional measurements, which is categorized according to detectable defect location and spatial resolution. Accordingly, optical methods can achieve very high measuring resolutions, in the range of nanometers when interferometry techniques are employed, but they can only inspect defects at

the surface (or through a surface opening). Eddy-current testing and ultrasonic techniques can detect defects within the volume if they are not located very deep inside the testing sample, but the one drawback is the limited spatial resolution of detection, which is in the millimeter range or some fraction of millimeters in the most optimal situations. In contrast, the best method for nondestructive inspection of complex structures and geometries inside the volume of a part is currently X-ray CT, with a resolution range from millimeters to micrometer ranges, and sub-micron levels in some special cases, e.g., by using synchrotron X-ray sources or with the help of focusing elements such as Fresnel zone plates or Kirkpatrick-Baez mirrors [9-12].

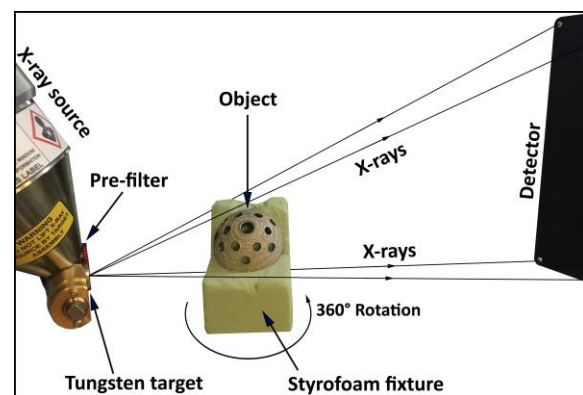


FIGURE 2. Basic setup for an X-ray CT scan. After collecting several radiographic images (or simply ‘projections’) taken from a large number of different angular positions around the specimen during a 360° rotation, with the aid of a reconstruction algorithm, it is possible to reconstruct a three-dimensional image of the object detailing all of its internal and external features.

X-RAY COMPUTED TOMOGRAPHY

Since CT shows several advantages as a non-destructive method for acquiring structural characterization of both internal and external geometries of AM parts, it is often considered the only viable option to extract component dimensions of internal or hidden features that are inaccessible to well-established metrology tools [13-16]. This makes CT technology a good partner in the “3D printing revolution” for the study and inspection of AM products. Thus X-ray CT is typically used to detect porosity and cracks in AM parts, dimensional deviations from computer-aided design (CAD) models, and powder residues or inclusions left inside the AM built part. Figure 2, for example, shows a typical

CT setup featuring the scanning of an AM acetabular hip prosthesis cup made of Ti-6Al-4V and produced by an electron beam melting process, which has a prescribed non-uniform lattice structure forming struts over the surface with an interconnected porosity (to stimulate bone adhesion). In recent work [17], along with the use of image processing software such as MATLAB and ImageJ, X-ray CT has been used to provide quality inspection and characterization of the porous structure that affects the implant's fixation. In such an application, the non-destructive and non-contact nature of CT shows a clear advantage over other inspection methods, such as tactile CMMs and optical systems; it provides an analysis of interconnectivity of the porous structure, the standard deviation of the size of the pores and struts, and the local thickness of the lattice structure in its size and spatial distribution [17]. Additional examples of the X-ray CT usage for inspection of AM parts and processes can be found elsewhere, e.g., [18-19].

In general, tactile CMMs or optical measuring instruments like laser scanners are limited to the measurement of the external surface of an AM part. In addition, tactile CMMs can produce compressive stresses and friction during sliding that could produce wear at the surface [20-21]. In contrast, X-ray CT eliminates the above difficulties because it is a non-contact technique that can access internal features. Since the principles of X-ray CT—when used for obtaining dimensional measurements—differ substantially from tactile CMMs and optical or light-based systems, each technique has its own distinctive attributes that accentuate and limit their capabilities and range of applications. Table 1 shows a comparative list of some of the main factors influencing the metrological performance of tactile CMMs, optical systems, and X-ray CT machines. Naturally, the capability of defect detection by X-ray CT depends very much on the part's size, complexity, and material, but in principle, high scanning metrological resolutions in the order of 10 or 5 μm are possible [22-23].

Table 1. Main influencing factors that can affect the performance of optical, tactile, and X-ray CT inspection systems for dimensional measurement tasks [21].

Optical	Tactile	X-ray CT
Resolution limit (diffraction)	Diameter of stylus tip	Resolution and magnification
Optical magnification	Stylus shaft length and stiffness	Image contrast/signal-to-noise
Sensor receptor gain/reading	Sampling strategy	Detector gain/sensitivity
Surface slope or tilt	Number of probing points	Number of projections
Surface roughness/finish	Surface characteristics	X-rays energy spectrum
Object geometry and size	Object geometry and size	Object geometry and size
Illumination type/intensity	Object clamping/mounting	Object orientation/tilt
Material transparency/translucency	Probing speed/force/direction	Material composition
Surface reflectivity/opacity	Probe calibration	Scaling calibration
Edge sub-pixel interpolation	Fitting algorithms	Edge sub-voxel interpolation
Environmental conditions	Environmental conditions	Environmental conditions

DEFECT ANALYSIS WITH X-RAY CT

Recently, there has been a growing interest in the determination of material porosity in AM manufactured parts, e.g., see [24-26]. In cases of AM processes that use metal powders, the powder typically comes in solid grains, and if such grains are fine, the powder particles are within the size range of 15 μm to 150 μm [27]. However, some of the powder particles might be hollow, i.e., some of them may come with pores inside them, as can be seen in Figure 3. In addition to porosity, particle size distribution, morphology, heterogeneity, geometry, and grain microstructure are of particular interest in AM powders [27-31]. There are certain anomalies

that could potentially induce defects in powder-based AM parts. For example, powders with uniform size distribution are known to promote homogeneous melting, and good interlayer bonding [29]. In contrast, powders prone to form grain agglomerates may assume irregular shapes or lead to porosity in the component when metal AM laser or electron beam melting is used. As can be seen from the right image (in Figure 3), most grains of aluminum powder seems to have shapes that are non-spherical, of different size, and irregular morphology. Several of them are agglomerated in small clusters. In addition, several grains show porosity channels or voids in their internal structure. In contrast, as

seen on the left side of Figure 3, Inconel powder grains seem to be consistently round, almost identical in size, and relatively small as compared to the aluminum powder. However, some of the Inconel powder grains seem to still exhibit micro-porosity structures inside them. The presence of these channels or microstructures in the powder material could potentially influence the porosity percentage of a finished AM part built from such material or induce fractures and cracks inside by the lack of fusion voids. In the current literature, there are several studies on the influence of powder related parameters—such as particle size, uniformity, shape and distribution, or grain porosity—on the final result of an AM process, including evidence of part defects induced by unmolten powder particles or agglomeration of powder trapped in the inside, e.g., see [28-33]. Figure 5 illustrates the application of X-ray CT for the inspection of porosity in a finished AM part, revealing a variety of voids of different size, shape, and frequency distribution.

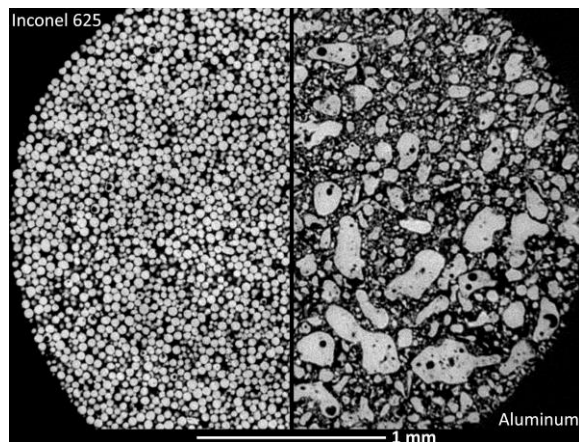


FIGURE 3. A composed X-ray CT image of two different raw AM powders that reveals porosity inside the AM particles. Left: nickel-chromium alloy (Inconel 625). Right: aluminum 225 mesh (65 μm). Data were obtained using identical CT geometrical configuration (with a Nikon XTH 225 ST system) but different X-ray power settings: 93 kV and 50 μm (and 1 s integration time) for the Inconel sample, and 60 kV and 95 μA (and 1.4 s integration time) for the aluminum powder.

In a broader sense, when testing and qualifying AM components, it is vital to understand defects effects on the structural performance and overall quality of the final product [4, 24-26]. For example, along with an additional AM cylindrical rod part acting as ‘witness coupon’, the turbine

blade from Figure 5 has previously been used to illustrate the usefulness of CT data on the study of property/characteristics transfer from a ‘witness coupon’ to a component (made at the same time and of the same material as the actual component). Initial results of these studies, as presented elsewhere [4], show that non-fracture-critical properties may have a much lower dependency on the defect distribution in comparison to fatigue.

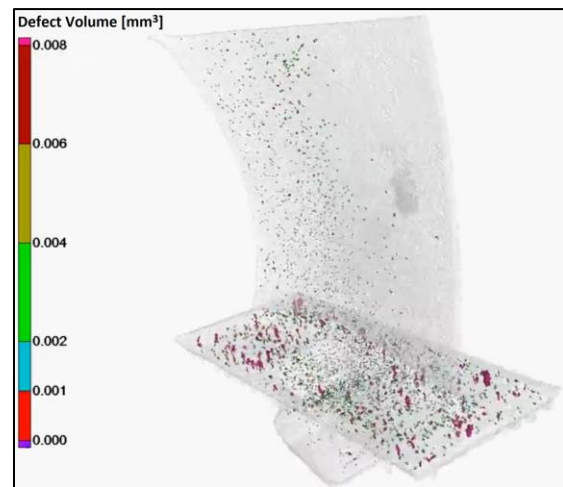


FIGURE 5. X-ray CT porosity analysis of an AM turbine blade, of approximately 5.5 mm height, made of Ti-6Al-4V, and produced by electron beam melting process. The color-coded bar features the presence of defects in different ranges of size.

In actuality, measuring and characterizing each internal defect from the CT data can be a daunting task, mainly due to the sheer quantity of data that resides in high-resolution, volumetric CT datasets. Fortunately, many tools are available to assist in the measurement and analysis of large quantities of internal defects, e.g., see [34-37], and automated defect recognition algorithms are increasingly being implemented in practice, including tools for image processing and statistical analysis techniques that catalogue and summarize defects inside a particular volume. In the end, to make informed decisions about whether or not to pass or fail an AM component, one will need to rely upon comprehensive knowledge of the defects and their relationship to material properties and input process parameters. Additional testing and more advanced analysis may be required to establish the proper baseline, in order to understand what level of defects constitutes a failed part.

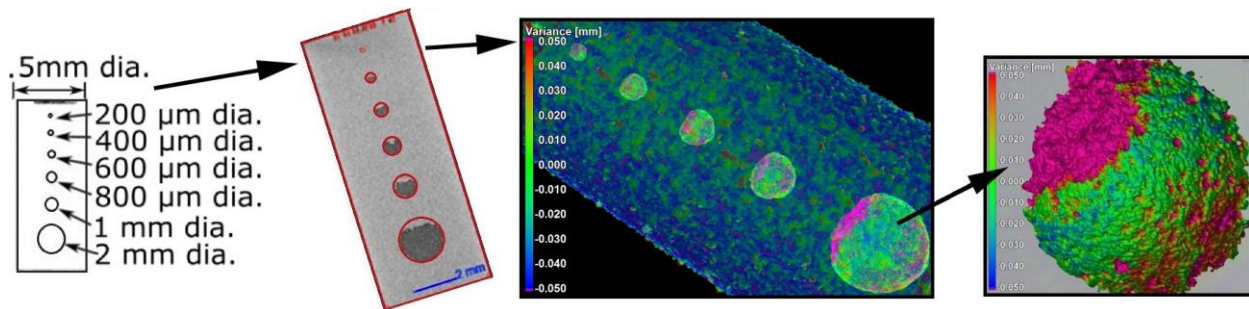


FIGURE 6. X-ray CT inspection of an AM test part (designed and fabricated by NIST) with an internal structure intended to recreate flaws inside the part. The test part was made of a nickel-chromium alloy (Inconel 625) and produced by a laser-based powder bed fusion process. The color-coded bar features dimensional deviations in the geometry of the AM part when compared to the nominal intended design, i.e., with respect to the reference/nominal geometry of the CAD model.

DIMENSIONAL METROLOGY OF AM PARTS

CT technologies are particularly useful to study the outcome of AM processes. Assessments of performance, for example, can be contrasted between different manufacturing methods by the nondestructive measurement of the AM parts. The appeal of CT in dimensional metrology is evident in the recent growth of surveys in the field, e.g., see [38-41], where X-ray CT is considered a tool for dimensional quality control and geometrical tolerance verification of industrial components. One of the critical steps in evaluating AM performance of different systems would be to intentionally place simulated flaws of varied geometrical shapes inside the AM part designs. Then, after manufacturing, these features can be evaluated to identify the limits inherent to the AM process. Figure 6 presents one of these case studies that has been performed in collaboration with NIST (the National Institute of Standards and Technology) [37]. From the measurements of actual to nominal comparison, variations in dimensional geometry were detected for the AM parts with deviations up to ± 0.1 mm with respect to reference geometry (nominal data). Material inclusions in the internal cavities were also detected as remnants from the AM process. The design of test parts for the evaluation of AM machines' dimensional performance has also been a subject of recent investigations. One example is the test object shown in Figure 7, which was first proposed by NIST [42]. Given its original geometry and large dimensions, such an object was designed so that the final AM part could be measured by CMM and surface texture instruments. However, it is not surprising to see researchers trying to use it for X-ray CT measurement, which is challenging with metals.

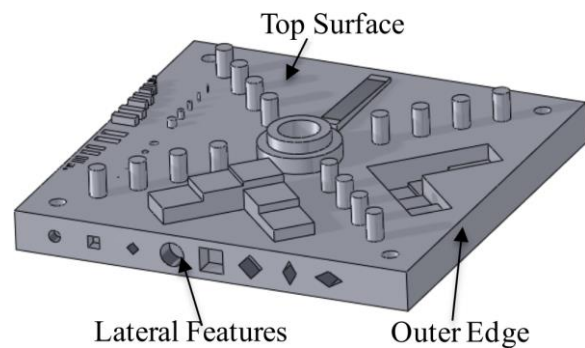


FIGURE 7. Solid model of a test part designed and proposed by NIST for AM performance evaluation and standardization purposes [42].

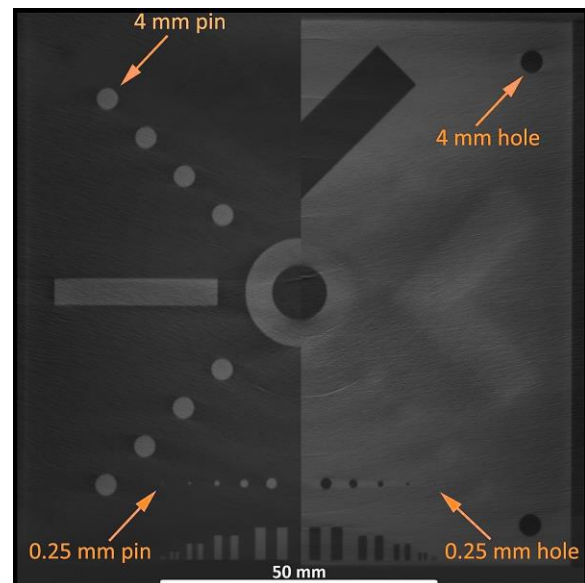


FIGURE 8. CT image of an AM built prototype of the NIST test part. The arrows in the figure point toward features and dimensions from nominal geometry of the NIST design (see Figure 7).

Metal parts often scatter X-rays, which may disrupt the CT reconstructions and produce unwanted artifacts in the data. Using a 2D fan beam of X-rays and a linear detector can reduce the scattering of X-rays and allow high quality CT data to be obtained. A highly penetrating beam, from a small X-ray source, is required for scanning highly absorbent materials such as nickel alloys. Figure 8 shows an image obtained by 2D fan beam X-ray CT of an AM prototype, made of Inconel 625, for the NIST test part. A Nikon XTH 450 system was used for CT data acquisition. For such sample, 420 kV was used with several millimeters of tin and copper filters to harden the polychromatic X-ray beam and reduce beam hardening artifacts. The image in Figure 8 was composed by joining two different halves of CT sectional slices, both extracted from equal separation distance from the 'top surface' but opposite in direction: the left half is 0.4 mm above from the 'top surface' and the left half is 0.4 mm below from the same surface. In future work, the authors plan to evaluate dimensional geometry assessments of the NIST test part based on three-dimensional CT data.

NEW PERSPECTIVES

One important focus of current research efforts in AM is to understand how process parameters influence defect formation in AM builds. Like any manufacturing process, there exists an endless combination of input parameters (i.e., laser power, build speed, layer thickness, etc.) that can be chosen by the user before, during, and after the manufacturing process [43]. A complete, universal understanding of all of these inputs and how they affect the overall performance of a component is difficult to determine. Mathematical models based on empirical test data are one of the tools most commonly used for understanding the effects of AM process parameters [44]. To this end, statistical analysis of defect data can be used to determine the quality of a build. Given the correct design of experiments, optimization of process parameters can be performed in order to minimize the quantity and severity of internal defects. Given the vast amount of input parameters in many AM methods, this is not a speedy process. In many cases, it may require a large number of samples and large quantities for CT inspection. To shorten the time and effort in this process, some more recent research is leveraging advanced analytical methods such as artificial intelligence and machine learning algorithms [45]. These tools have the ability to

analyze the complete defect data for a large set of samples in order to uncover hidden patterns and dependencies that may exist between the defects and input parameters, not apparent in other methods. There has also been growing interest in finding new in-situ techniques that can collect in-process data to feedback into the AM systems. This process would allow corrective actions by optimizing the parameters during the AM process. Integrating NDT techniques capable of sub-surface inspection during the AM process, such as X-ray CT, seem to be a challenging task, although some progress has been recently reported by using simple X-ray imaging [46-47] and X-ray phase contrast [48]. On the other hand, there has been growing interest in the possibility of using X-ray CT data for obtaining surface topography measurements, which would allow obtaining surface data of AM internal geometries without destroying or sectioning the part. This has already been reported as possible in some pioneer work performed elsewhere [49-52].

CONCLUSIONS

It is critical to understand the role of quality control and inspection techniques so that the safety and integrity of AM parts can be qualified. CMMs and optical-based systems cannot access internal geometries, but X-ray CT is particularly suited to this purpose. While other techniques like ultrasonic and eddy current may be sufficient at finding defects in particular locations inside a part, only X-ray CT provides a full volumetric map of the material density distribution which shows these defects. Various examples of the use of X-ray CT to support AM qualification have been shown in this paper. A simple workflow optimization process to improve design and production of AM parts could be as follows: knowing the deviation from the intended form and dimensions of the design helps to quickly refine the model for an AM part (see Figure 9).

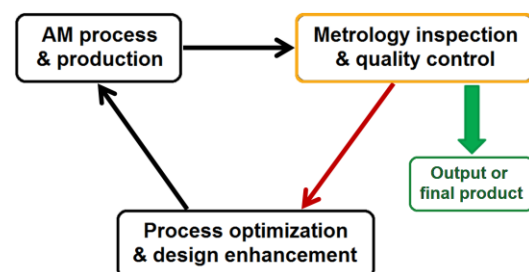


FIGURE 9. An iterative and cyclical optimization process for design and production in AM parts.

REFERENCES

- [1] A. A. Hassen and M. M. Kirka, "Additive Manufacturing: The rise of a technology and the need for quality control and inspection techniques," *Materials Evaluation*, vol. 76, no. 4, pp. 439-453, 2018.
- [2] Q. Y. Lu and C. H. Wong, "Additive manufacturing process monitoring and control by non-destructive testing techniques: challenges and in-process monitoring," *Virtual and Physical Prototyping*, vol. 13, no. 2, pp. 39-48, 2018.
- [3] S. A. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue and C. Charitidis, "Additive manufacturing: scientific and technological challenges, market uptake and opportunities," *Materials Today*, vol. 21, no. 1, pp. 22-37, 2018.
- [4] M. Seifi, M. Gorelik, J. Waller, N. Hrabe, N. Shamsaei, S. Daniewicz and J. Lewandowski, "Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification," *The Journal of The Minerals, Metals & Materials Society*, vol. 69, no. 3, pp. 439-455, 2017.
- [5] Y. Huang, M. C. Leu, J. Mazumder and A. Donmez, "Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations," *Journal of Manufacturing Science and Engineering*, vol. 137, no. 1, p. 014001 (10p), 2014.
- [6] C. Dordlofva and P. Törlind, "Qualification challenges with additive manufacturing in space applications," in *Proc. of 28th Annual Solid Freeform Fabrication Symposium*, Austin, Texas (USA), pp. 2699-2712, 2017.
- [7] J. A. Slotwinski, "Additive manufacturing: Overview and NDE challenges," in *AIP Conference Proceedings, 40th Annual Review of Progress in Quantitative Nondestructive Evaluation*, Baltimore, Maryland (USA), Vol. 1581, No. 1, pp. 1173-1177, 2014.
- [8] R. B. Bergmann, F. T. Bessler and W. Bauer, "Non-Destructive Testing in the Automotive Supply Industry - Requirements, Trends and Examples Using X-ray CT," in *9th European Conference on Non Destructive Testing*, Berlin (Germany), 2006.
- [9] E. Maire and P. J. Withers, "Quantitative X-ray tomography," *International Materials Reviews*, vol. 59, no. 1, pp. 1-43, 2014.
- [10] P. J. Withers, "X-ray nanotomography," *Materials Today*, vol. 10, no. 12, pp. 26-34, 2007.
- [11] G. E. Ice, J. D. Budai and J. W. L. Pang, "The race to X-ray microbeam and nanobeam science," *Science*, vol. 334, no. 6060, pp. 1234-1239, 2011.
- [12] J. Kastner and C. Heinzl, "X-ray Computed Tomography for Non-destructive Testing and Materials Characterization," in *Integrated Imaging and Vision Techniques for Industrial Inspection (Liu Z., Ukida H., Ramuhalli P., Niel K., editors)*, London, England (UK), Springer, 2015, pp. 227-250.
- [13] L. De Chiffre, S. Carmignato, J. P. Kruth, R. Schmitt and A. Weckenmann, "Industrial applications of computed tomography," *CIRP Annals - Manufacturing Technology*, vol. 63, pp. 655-677, 2014.
- [14] J. P. Kruth, M. Bartscher, S. Carmignato, R. Schmitt, L. De Chiffre and A. Weckenmann, "Computed tomography for dimensional metrology," *CIRP Annals - Manufacturing Technology*, vol. 60, pp. 821-842, 2011.
- [15] H. Villarraga-Gómez, E. P. Morse, R. J. Hocken and S. T. Smith, "Dimensional metrology of internal features with X-ray computed tomography," in *29th ASPE Annual meeting*, Boston, MA, 684-689, 2014.
- [16] H. Villarraga-Gómez, C. Lee, S. P. Charney, J. A. Tarbutton and S. T. Smith, "Dimensional metrology of

- complex inner geometries built by additive manufacturing," in *ASPE Spring Topical Meeting*, Raleigh, NC, 164-169, 2015.
- [17] N. Kourra, J. M. Warnett, A. Attridge, G. Dibling, J. McLoughlin, S. Muirhead-Allwood, R. King and M. A. Williams, "Computed tomography metrological examination of additive manufactured acetabular hip prosthesis cups," *Additive Manufacturing*, vol. 22, pp. 146-152, 2018.
- [18] A. Thompson, I. Maskery and R. K. Leach, "X-ray computed tomography for additive manufacturing: a review," *Measurement Science and Technology*, vol. 27, p. 072001 (17pp), 2016.
- [19] A. Thompson, D. McNally, I. Maskery and R. K. Leach, "X-ray computed tomography and additive manufacturing in medicine: a review," *Int. J. Metrol. Qual. Eng.*, vol. 8, no. 17, pp. 1-15, 2017.
- [20] H. Villarraga-Gómez, C. Lee and S. T. Smith, "Dimensional metrology with X-ray CT: A comparison with CMM measurements on internal features and compliant structures," *Precision Engineering*, vol. 51, pp. 291-307, 2018.
- [21] H. Villarraga-Gómez, PhD Dissertation: Studies of Dimensional Metrology with X-ray CAT Scan, Department of Physics and Optical Science: The University of North Carolina at Charlotte, 2018.
- [22] S. Carmignato, A. Pierobon, P. Rampazzo, M. Parisatto and E. Savio, "CT for Industrial Metrology - Accuracy and Structural Resolution of CT Dimensional Measurements," in *4th Conference on Industrial Computed Tomography (iCT)*, Wels, Austria, 2012.
- [23] F. Zanini and S. Carmignato, "Two-spheres method for evaluating the metrological structural resolution in dimensional computed tomography," *Measurement Science and Technology*, vol. 28, p. 114002 (9pp), 2017.
- [24] J. A. Slotwinski, E. J. Garboczi and K. M. Hebenstreit, "Porosity measurements and analysis for metal additive manufacturing process control," *Journal of research of the National Institute of Standards and Technology*, vol. 119, pp. 494-528, 2014.
- [25] W. W. Wits, S. Carmignato, F. Zanini and T. H. Vaneker, "Porosity testing methods for the quality assessment of selective laser melted parts," *CIRP annals*, vol. 65, no. 1, pp. 201-204, 2016.
- [26] P. Hermanek, F. Zanini, S. Carmignato and E. Savio, "X-ray computed tomography for additive manufacturing: Accuracy and porosity measurements," in *ASPE/euspen 2016 Summer Topical Meeting*, Raleigh, NC (USA), 2016.
- [27] J. A. Slotwinski, E. J. Garboczi, P. E. Stutzman, C. F. Ferraris, S. S. Watson and M. A. Peltz, "Characterization of metal powders used for additive manufacturing," *Journal of research of the National Institute of Standards and Technology*, vol. 119, pp. 460-493, 2014.
- [28] F. H. Kim, S. P. Moylan, E. J. Garboczi and J. A. Slotwinski, "Investigation of pore structure in cobalt chrome additively manufactured parts using X-ray computed tomography and three-dimensional image analysis," *Additive Manufacturing*, vol. 17, pp. 23-38, 2017.
- [29] T. DebRoy, H. L. Wei, J. S. Zuback, T. Mukherjee, J. W. Elmer, J. O. Milewski, A. M. Beese, A. Wilson-Heid, A. De and W. Zhang, "Additive manufacturing of metallic components – Process, structure and properties," *Progress in Materials Science*, vol. 92, pp. 112-224, 2017.
- [30] W. J. Sames, F. A. List, S. Pannala, R. R. Dehoff and S. S. Babu, "The metallurgy and processing science of metal additive manufacturing," *International Materials Reviews*, vol. 65, no. 5, pp. 315-360, 2016.

- [31] A. T. Sutton, I. C. S. Kriewal, M. C. Leu and J. W. Newkirk, "Powders for additive manufacturing processes: Characterization techniques and effects on part properties," in *Proc. of 26th Annual International Solid Freeform Fabrication Symposium—An Additive Manufacturing Conference*, Austin, Texas (USA), pp. 1004-1030, 2016.
- [32] N. T. Aboulkhair, N. M. Everitt, I. Ashcroft and C. Tuck, "Reducing porosity in AlSi10Mg parts processed by selective laser melting," *Additive Manufacturing*, vol. 1, pp. 77-86, 2014.
- [33] S. Gorsse, C. Hutchinson, M. Gouné and R. Banerjee, "Additive manufacturing of metals: a brief review of the characteristic microstructures and properties of steels, Ti-6Al-4V and high-entropy alloys," *Science and Technology of advanced Materials*, vol. 18, no. 1, pp. 584-610, 2017.
- [34] H. Villarraga-Gómez, C. Lee, T. Corbett, J. A. Tarbutton and S. T. Smith, "Assesing additive manufacturing processes with X-ray CT metrology," in *ASPE Spring Topical Meeting*, Raleigh, NC, 2015.
- [35] H. Villarraga-Gómez, C. Lee, S. P. Charney, J. A. Tarbutton and S. T. Smith, "Dimensional metrology of complex inner geometries built by additive manufacturing," in *ASPE Spring Topical Meeting*, Raleigh, NC, 2015.
- [36] H. Villarraga-Gómez, M. Seifi, Y. Uchiyama, A. Ramsey and J. J. Lewandowski, "Assessing the structural integrity of additive manufactured metal parts with X-ray CT," in *ASPE/euspen 2016 Summer Topical Meeting*, Raleigh, NC (USA), 2016.
- [37] F. H. Kim, H. Villarraga-Gómez and S. P. Moylan, "Inspection of embedded internal features in additively manufactured metal parts using metrological x-ray computed tomography," in *ASPE/euspen 2016 Summer Topical Meeting*, Raleigh, NC (USA), 2016.
- [38] J. P. Kruth, M. Bartscher, S. Carmignato, R. Schmitt, L. De Chiffre and A. Weckenmann, "Computed tomography for dimensional metrology," *CIRP Annals - Manufacturing Technology*, vol. 60, no. 2, pp. 821-842, 2011.
- [39] H. Villarraga-Gómez, "Seeing is believing: X-ray computed tomography for quality control," *Quality Magazine*, vol. 55, no. 6, pp. 20-23, 2016.
- [40] S. Kasperl, J. Hiller and M. Krumm, "Computed tomography metrology in industrial research and development," *Materials Testing*, vol. 51, no. 6, pp. 405-411, 2009.
- [41] L. De Chiffre, S. Carmignato, J. P. Kruth, R. Schmitt and A. Weckenmann, "Industrial applications of computed tomography," *CIRP Annals - Manufacturing Technology*, vol. 63, no. 2, pp. 655-677, 2014.
- [42] S. Moylan, J. Slotwinski, A. Cooke, K. Jurrens and M. A. Donmez, "An additive manufacturing test artifact," *Journal of research of the National Institute of Standards and Technology*, vol. 119, pp. 429-459, 2014.
- [43] M. Yakout, A. Cadamuro, M. A. Elbestawi and S. C. Veldhuis, "The selection of process parameters in additive manufacturing for aerospace alloys," *The International Journal of Advanced Manufacturing Technology*, vol. 92, no. 5-7, pp. 2081-2098, 2017.
- [44] I. Baturynska, O. Semeniuta and K. Martinsen, "Optimization of process parameters for powder bed fusion additive manufacturing by combination of machine learning and finite element method: a conceptual framework," in *11th CIRP Conference on Intelligent Computation in Manufacturing Engineering*, Gulf of Naples (Italy), 6p, 2017.
- [45] M. Ferguson, R. Ak, Y. T. Lee and K. H. Law, "Automatic localization of casting defects with convolutional neural

- networks," in *Proc. of IEEE International Conference on Big Data (Big Data)*, Boston, MA (USA), 1726-1735, 2017.
- [46] C. L. Leung, S. Marussi, R. C. Atwood, M. Towrie, P. J. Withers and P. D. Lee, "In situ X-ray imaging of defect and molten pool dynamics in laser additive manufacturing," *Nature communications*, vol. 9, no. 1, pp. 9pp, 1355, 2018.
- [47] N. P. Caltà, J. Wang, A. M. Kiss, A. A. Martin, P. J. Depond, G. M. Guss, V. Thampy, A. Y. Fong, J. N. Weker, K. H. Stone and C. J. Tassone, "An instrument for in situ time-resolved X-ray imaging and diffraction of laser powder bed fusion additive manufacturing processes," *Review of Scientific Instruments*, vol. 89, pp. 8pp, 055101, 2018.
- [48] Y. Kawahito and H. Wang, "In-situ observation of gap filling in laser butt welding," *Scripta Materialia*, vol. 154, pp. 73-77, 2018.
- [49] A. Thompson, N. Senin, C. Giusca and R. Leach, "Topography of selectively laser melted surfaces: a comparison of different measurement methods," *CIRP Annals*, vol. 66, no. 1, pp. 543-546, 2017.
- [50] A. Townsend, L. Pagani, P. Scott and L. Blunt, "Areal surface texture data extraction from X-ray computed tomography reconstructions of metal additively manufactured parts," *Precision Engineering*, vol. 48, pp. 254-264, 2017.
- [51] N. Senin, A. Thompson and R. K. Leach, "Characterisation of the topography of metal additive surface features with different measurement technologies," *Measurement Science and Technology*, vol. 28, pp. 12pp, 095003, 2017.
- [52] A. Thompson, N. Senin, I. Maskery, L. L. S. Körner and R. Leach, "Internal surface measurement of metal powder bed fusion parts," *Additive Manufacturing*, vol. 20, pp. 126-133, 2018.

A SYSTEMS APPROACH TO PREDICTION AND MITIGATION OF RADIOGRAPHIC BLUR

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INTRODUCTION

This paper presents theory and methods to better understand the sources of blur in a X-ray projection imaging system depicted in Figure 1 [1]. The proposed approach provides deeper insight into the mechanisms that cause blur, in order to reduce blur via hardware and algorithmic improvements. Blur reduction improves data analysis and interpretation by providing sharper images with less noise from projection X-ray systems. This leads to improved medical diagnostics and part metrology among many other applications.

tions throughout the X-ray imaging system. In X-ray imaging, the blur in radiographs is modeled as a combination of blur from the source, detector, system motion, and object scatter. The magnitude of contribution of each individual source of blur varies with the source to object distance (SOD) and object to detector distance (ODD). Hence, by acquiring radiographs at different object locations, we are able to computationally extract the analytical form of the point spread function (PSF) of each component of blur.

Knowledge of the PSF of each individual blur component allows us to predict the blur in radiographs throughout the full possible operational parameter space, including at different source-object-detector configurations prior to acquiring images. More importantly, determining the dominant blur source will allow the experimentalist to decide on the best strategy to reduce the overall system blur. Furthermore, extracting the analytical PSF enables us to use deblurring algorithms to sharpen the radiographs after acquiring the X-ray imaging measurements.

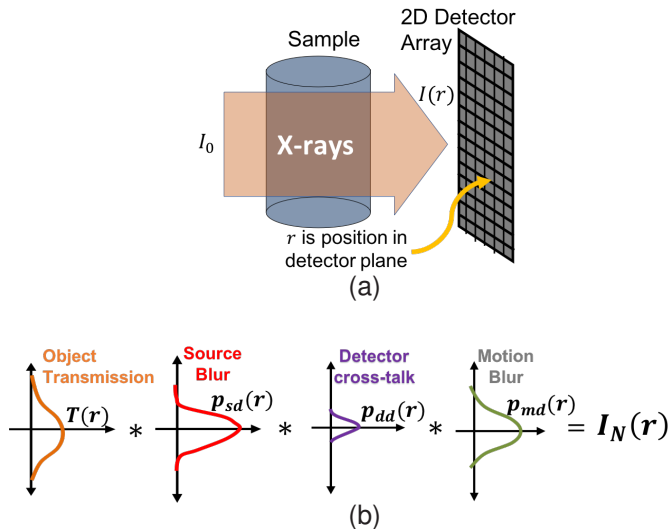


FIGURE 1. (a) Experimental setup of the X-ray imaging system. (b) Normalized radiograph given by the convolution (denoted by $*$) of the transmission function with the PSFs of multiple sources of blur.

There are multiple sources of blur in an X-ray imaging system. We apply a systems approach to understand blur by developing a model and experimental procedure that enables simultaneous consideration of the multiple blur contribu-

The X-ray system used in this study is the Zeiss Xradia 510 Versa. This commercial micro CT system has a Tungsten target with bremsstrahlung spectral characteristics. The accelerating voltage was selected to be 160 kV while the tube current was $62.5\mu\text{A}$ which resulted in an average flux of $1.37 \times 10^{11} \text{ counts mA}^{-1} \text{ nstr}^{-1} \text{ sec}^{-1}$. The X-ray detector consists of an optically coupled thallium-doped cesium iodide scintillator and 5 MP CCD with a $13.5\mu\text{m}$ pixel size, 16-bit depth, and a maximum dark current noise of about $12 \text{ counts sec}^{-1}$. Bright (image without object) and dark field (X-rays off) images were acquired to appropriately normalize each radiograph image of the object. All radiographs were acquired at a $20\times$ magnification resulting in an effective pixel size of $0.675\mu\text{m}$.

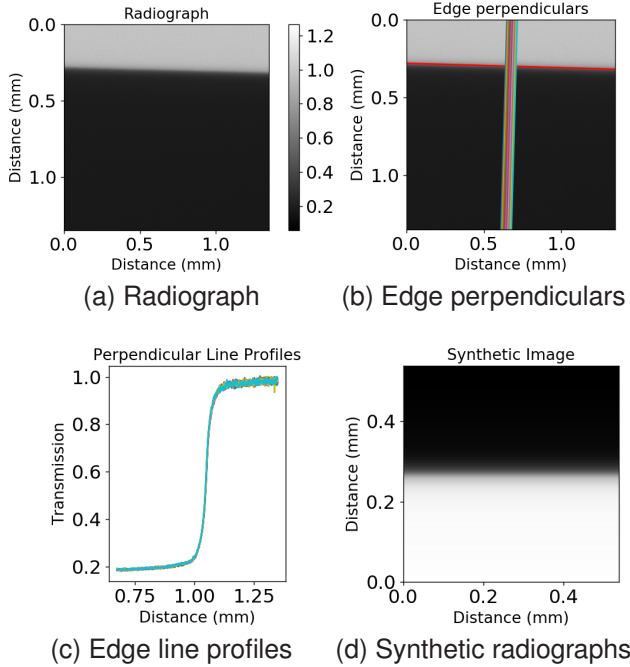


FIGURE 2. (a) Normalized radiograph of a Tungsten edge at a X-ray source to object distance of 12mm and a source to detector distance of 74mm. (b) Tungsten edge highlighted in red and several colored lines drawn perpendicular to this edge. (c) Values along the perpendicular lines shown in (b). (d) Synthetic image generated from (c) that is used to estimate the blur PSFs.

BLUR ESTIMATION

In this section, we present our X-ray transmission and blur model. Then, we discuss an experimental procedure to computationally extract the size and shape of each blur PSF.

Forward Model

Our forward model for the X-ray imaging system expresses the blur in the radiograph as the convolution of a object transmission function with the PSFs of source, detector, and system motion [1]. Let $p_{sd}(r)$, $p_{dd}(r)$, $p_{md}(r)$ be the point spread functions (PSF) due to blur from the source, detector, and system motion on the detector plane as shown in Figure 1(b). Then, the normalized radiograph is given by,

$$I_N(r) = \frac{I(r)}{I_0} = T(r) * p_{sd}(r) * p_{dd}(r) * p_{md}(r) \quad (1)$$

where $I(r)$ is the measurement with the object, I_0 is the measurement without the object, $*$ denotes 2D convolution, and r is the position vector on the 2D detector plane. The object transmission function $T(r)$ accounts for the photons that emerge

from the object without any material interaction while also including the photons from Coherent single scatter. Let $\mu_{tot}(r)$ and $\mu_c(r)$ be the total and coherent scatter cross-sections respectively. Then, the transmission function $T(r)$ is,

$$T(r) = e^{-\mu_{tot}(r)DL} + C(r, D, L) * p_{cd}(r), \quad (2)$$

where D is the material density and L is the object width. The term $e^{-\mu_{tot}(r)DL}$ accounts for the fraction of photons that emerge from the object without any material interaction and $C(r, D, L)$ accounts for the fraction of photons that undergo coherent single scatter. The PSF $p_{cd}(r)$ models the blur due to coherent single scatter on the detector plane. The scatter blur is approximated as a spatially invariant phenomena under the paraxial approximation. Instead of estimating the scatter parameters from calibration data, we use tabulated theoretical values for $C(r, D, L)$ and $p_{cd}(r)$. Data driven estimation of scatter model parameters is beyond the scope of this paper and will be addressed in a future publication. In this paper, we only address the problem of estimating the blur PSFs $p_{sd}(r)$, $p_{dd}(r)$, and $p_{md}(r)$ from calibration data.

Modeling PSF using Exponential Densities

The source PSF as evaluated at the source plane is modeled using an isotropic exponential density function with the following analytical form,

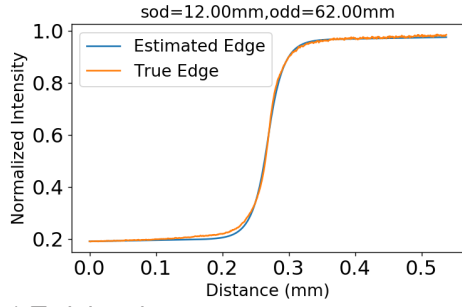
$$p_{ss}(r'_s) = \frac{1}{Z} \exp \left\{ -\frac{1.386}{W_s} |r'_s| \right\} \quad (3)$$

where $r'_s = (x'_s, y'_s)$ are the coordinates in the plane of the source, $|r'_s| = \sqrt{x'^2_s + y'^2_s}$ is the Euclidean norm of (x'_s, y'_s) , W_s is the full width half maximum (FWHM) of the PSF, and Z is a constant that normalizes $p_{ss}(r')$ to have unit integral over its domain. At the detector plane, the source blur gets magnified or demagnified depending on the source, object, and detector positions. At the detector plane, the source blur has the following form,

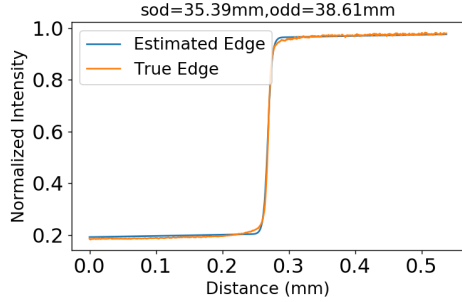
$$p_{sd}(r'_d) = \frac{1}{Z} \exp \left\{ -\frac{1.386}{W_s} \frac{z_{so}}{z_{od}} |r'_d| \right\} \quad (4)$$

where $r'_d = (x'_d, y'_d)$ are coordinates on the detector plane, $|r'_d| = \sqrt{x'^2_d + y'^2_d}$, z_{so} is the X-ray source to object distance, and z_{od} is the object to detector distance.

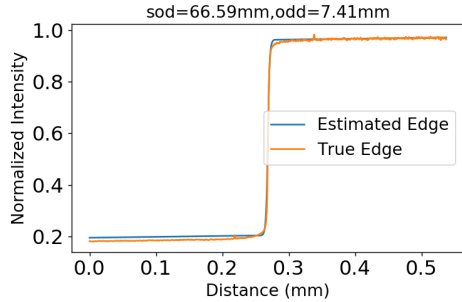
The detector blur has a more complex distribution and is modeled using a mixture distribution of



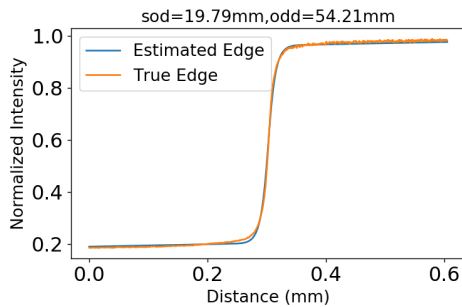
(a) Training data; $z_{so} = 12mm$, $z_{od} = 62mm$



(b) Training data; $z_{so} = 35.39mm$, $z_{od} = 38.61mm$



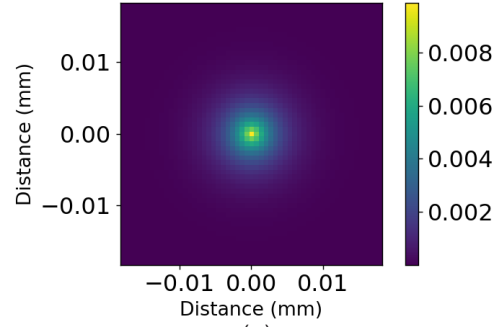
(c) Training data; $z_{so} = 66.59mm$, $z_{od} = 7.41mm$



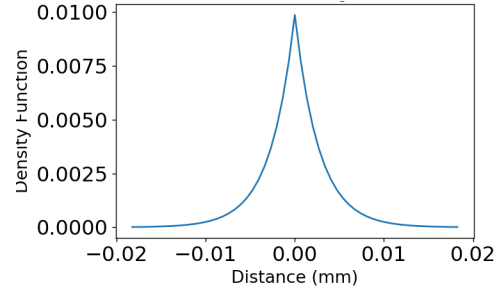
(d) Testing data; $z_{so} = 19.79mm$, $z_{od} = 54.21mm$

FIGURE 3. Figure 3 (a-d) demonstrates agreement between the true edge line profile and its estimate as predicted by our forward model for different source-object-detector configurations. (a-c) are used for training the blur model in equation (6). (d) demonstrates accuracy of the blur model for a system configuration not used during model estimation.

two exponential density functions. Similar to detector blur, blur due to system motion is invariant



(a)



(b)

FIGURE 4. Source PSF of equation (3). (a) 2D PSF of source blur and (b) Line profile through the center of the 2D PSF in (a). The FWHM of source PSF was estimated to be 0.0038mm which agrees well with the manufacturer provided value of 0.004 mm.

to the relative distances between source, object, and detector. Let $p_{dd}(r)$ and $p_{md}(r)$ denote the PSF of the blur due to detector and system motion on the detector plane respectively. Then, the combined effect of detector and system blur has the following analytical form,

$$p_{dd}(r'_d) * p_{md}(r'_d) = p \frac{1}{Z_1} \exp \left\{ -\frac{1.386}{W_{d1}} |r'_d| \right\} + (1 - p) \frac{1}{Z_2} \exp \left\{ -\frac{1.386}{W_{d2}} |r'_d| \right\} \quad (5)$$

where $r'_d = (x'_d, y'_d)$ is the coordinate vector on the detector plane, $|r'_d| = \sqrt{x_d'^2 + y_d'^2}$, W_{d1} and W_{d2} are the FWHM of the two exponential densities, and Z_{d1} and Z_{d2} are normalizing constants. Here, p and $1 - p$ are parameters that function as weights for the exponential density functions. The two exponential densities in the above mixture model are necessary to accurately model the detector PSF which has a immediate sharp drop-off away from the center pixel followed by a very long tail with significant energy that extends across many detector pixels.

Estimation of Blur PSF

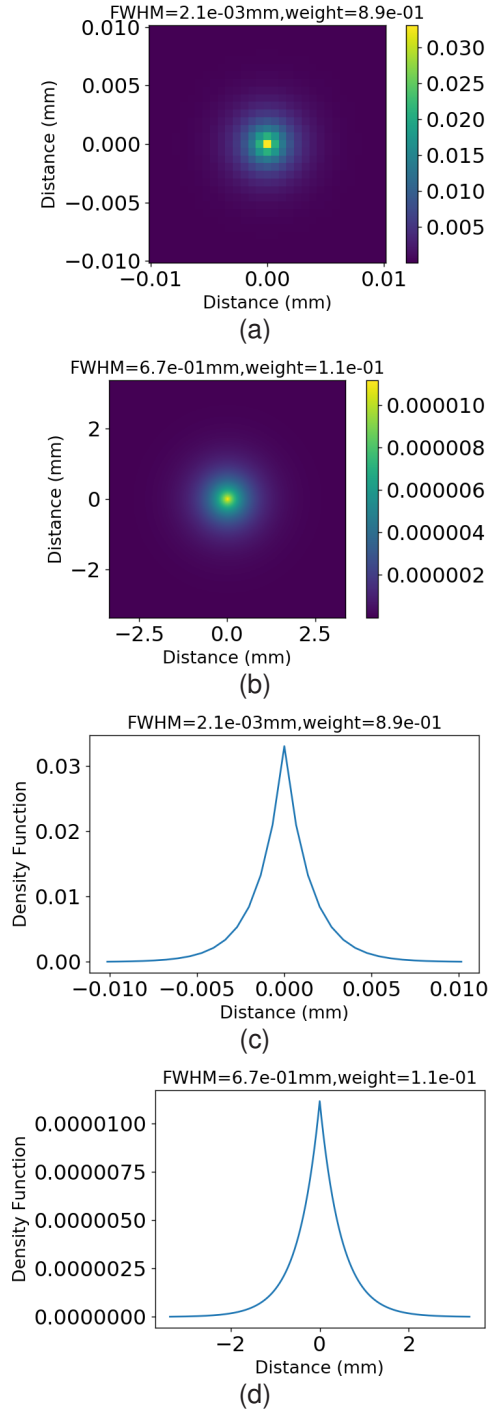


FIGURE 5. Detector and motion PSF of equation (5). The PSF is the weighted linear combination of the two exponential densities shown in (a) and (b). (c) and (d) are line profiles through the center of (a) and (b) respectively. PSF parameters are $W_{d1} = 0.0021\text{mm}$, $W_{d2} = 0.67\text{mm}$, and $p = 0.89$.

To extract each individual PSF, multiple radiographs $I_N(r)$ with varying levels of blur are ac-

quired at different object positions. The object is a uniform Tungsten plate with non-zero transmission such that it appears as a single straight edge in the radiographs as shown in Figure 2 (a). The edge is aligned slightly off horizontal so as to cut across pixelization rows for improved edge resolution. First, we extract, align, and average multiple line profiles perpendicular to the edge. Then, we form a synthetic 2D image of the Tungsten edge from the line profile by simply aligning the line profile vertically and copying it along the horizontal direction (Figure 2). Finally, we use numerical optimization techniques to estimate the best PSFs given the normalized synthetic radiographs and the model in equation (1) where the mass distribution is known.

The parameters of the source and detector PSFs are estimated by finding the parameter values that solve the following numerical optimization problem,

$$\begin{aligned} (\hat{W}_s, \hat{p}, \hat{W}_{d1}, \hat{W}_{d2}) &= \arg \min_{W_s, p, W_{d1}, W_{d2}} \left\{ \sum_i \|I_N^{(i)}(r) - \right. \\ &\quad \left. T^{(i)}(r) * p_{sd}^{(i)}(r) * p_{dd}(r) * p_{md}(r)\|^2 \right\} s.t. \\ T^{(i)}(r) &= e^{-\mu_{tot}(r)DL} + C(r, D, L) * p_{cd}^{(i)}(r) \\ p_{sd}^{(i)}(r) &= \frac{1}{Z} \exp \left\{ -\frac{1.386}{W_s} \frac{z_{so}^{(i)}}{z_{od}^{(i)}} |r| \right\} \end{aligned} \quad (6)$$

where $I_N^{(i)}(r)$ is the normalized radiograph at a source to object distance (SOD) of $z_{so}^{(i)}$ and object to detector distance (ODD) of $z_{od}^{(i)}$ and $(\hat{W}_s, \hat{p}, \hat{W}_{d1}, \hat{W}_{d2})$ are the estimated values of the parameters (W_s, p, W_{d1}, W_{d2}) respectively. The above optimization problem is solved using the Nelder-Mead Search Optimization procedure [2]. A comparison between $I_N^{(i)}(r)$ and its estimate $T^{(i)}(r) * p_{sd}^{(i)}(r) * p_{dd}(r) * p_{md}(r)$ after running the optimization procedure is shown in Figure 3. Three radiographs $I_N^{(i)}(r)$ at different source-object-detector configurations were used in the optimization of (6) and the corresponding line profiles of these radiographs are shown in Figure 3 (a,b,c). The line profile in Figure 3(d) demonstrates the accuracy of our model in predicting the blur for a system configuration that was not used during model estimation.

The Nelder-Mead optimization procedure solves (6) and provides best fit estimates for the blur parameters W_s, p, W_{d1} , and W_{d2} . Figure 4 and Fig-

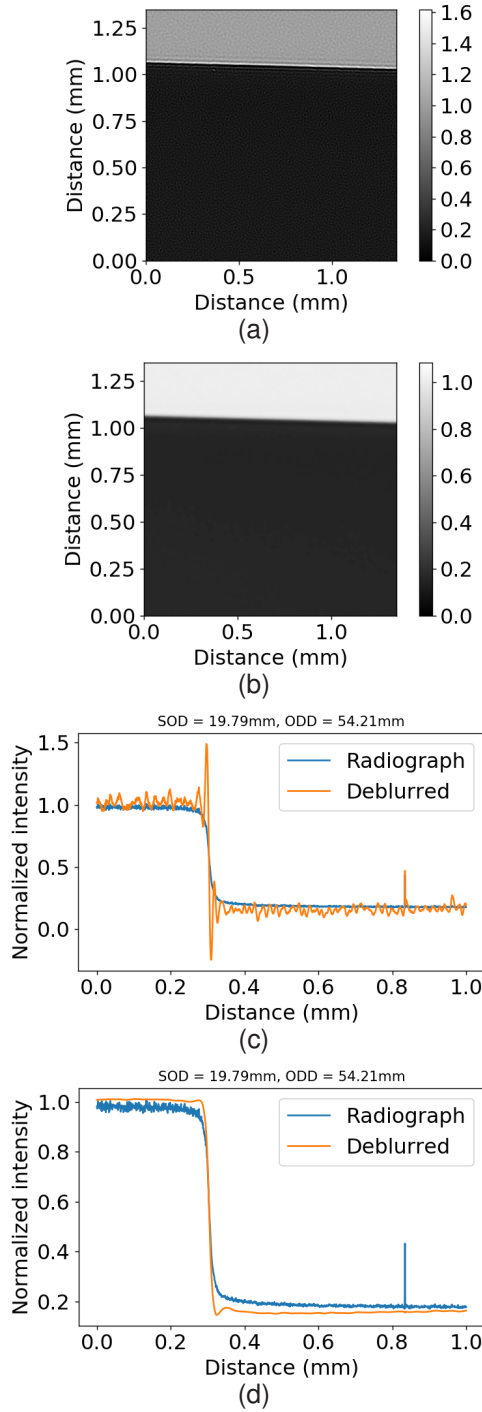


FIGURE 6. (a) and (b) shows the deblurred radiographs. (c) and (d) are line profiles across the edge in (a) and (b) respectively. (a,c) did not use any regularization ($\beta = 0$) while (b,d) used regularization ($\beta = 0.2$). Deblurring is done for a system configuration that was not used during model estimation. Deblurring with regularization not only sharpens the image but also reduces noise.

ure 5 show the estimated PSFs of the source blur and detector/motion blur respectively. The FWHM of the source PSF was estimated to be 3.8 micrometers by the optimizer, while the manufacturer specified FWHM was 4 micrometers. This demonstrates that the optimization approach is able to extract the FWHM of the source PSF using a purely data centric approach without any supervision. Importantly, the optimizer is capable of separating each individual blur contribution from images that contains blur from all sources. This framework also provides a means to capture the actual shape of the blur PSF from its components, as different PSF curve shapes can be tried over multiple fit parameters. A measure of mean-square error is used to drive the fitting of PSF shape and size. In our case, an exponential fit was found to provide much better alignment with data than the conventional gaussian curve.

BLUR REDUCTION

After estimating the parameters of the blur model, we use an algorithmic approach to remove blur in radiographs.

Iterative Deblurring Algorithm

To deblur a radiograph, we solve the following optimization problem -

$$\hat{T}(r) = \arg \min_{T(r)} \{ ||I_N(r) - T(r) * \hat{p}_{sd}(r) * \hat{p}_{dd}(r) * \hat{p}_{md}(r)||_{\Lambda}^2 + R(T(r)) \} \quad (7)$$

where $\hat{T}(r)$ is the deblurred image, $I_N(r)$ is the blurry radiograph, and $R(T(r))$ is the regularization cost function used to enforce sparsity in the recovery of $T(r)$. Expressions for $\hat{p}_{sd}(r)$ and $\hat{p}_{dd}(r) * \hat{p}_{md}(r)$ are derived by substituting $(\hat{W}_s, \hat{p}, \hat{W}_{d1}, \hat{W}_{d2})$ obtained from the optimization of (6) in equations (4) and (5). The regularization cost function is given by,

$$R(T(r)) = \beta \sum_{(i,j) \in \mathcal{N}} w_{ij} |T(r_i) - T(r_j)|^{1.2} \quad (8)$$

where β is the regularization strength parameter, $T(r_i)$ is a radiograph pixel at the i^{th} index location, w_{ij} is the weight parameter that is inversely proportional to the distance between pixels indexed by i and j , and $\mathcal{N}$ is the set of all pairs of neighboring voxel indices. Such a regularization function is widely used in many applications and is similar to the total-variation regularization albeit

with a 1.2-norm penalty function [3, 4]. The optimization problem in (7) is solved using conjugate gradient descent algorithm [5].

Input radiograph	0.08mm
Deblurred radiograph	0.022mm

TABLE 1. 95% to 5% drop-off width. This table quantifies the sharpness of each curve in Figure 6(d) by listing the distance between the points whose value is 95% and 5% of the difference between the maximum and minimum radiograph values. The 95% and 5% values were set to be 0.94 and 0.22 respectively. Clearly, the deblurred radiograph is sharper than the input radiograph.

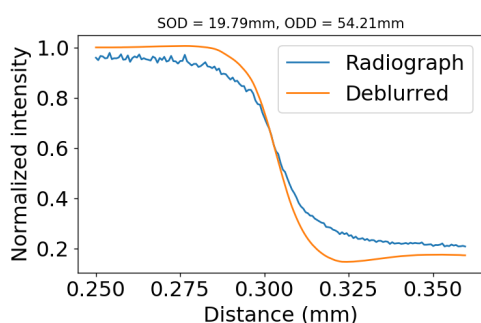


FIGURE 7. Plot that zooms into the step-transition region of Figure 6 (d) to provide easier visualization of the improvement in sharpness due to the deblurring operation using a regularization of $\beta = 0.2$.

Input radiograph	0.01005
Deblurred $\beta = 0$	0.03548
Deblurred $\beta = 0.2$	0.00083

TABLE 2. Noise standard deviation. This table shows the noise standard deviation for the input blurry radiograph, deblurred radiograph with $\beta = 0$, and deblurred radiograph with $\beta = 0.2$. Deblurring with regularization reduces noise in addition to improving sharpness.

To demonstrate the utility of the extracted PSFs in reducing blur, we show deblurring results obtained using (7) in Figure 6. Figure 6 (a,c) shows the deblurred radiograph without regularization obtained by setting $\beta = 0$ and Figure 6 (b,d) shows the deblurred radiograph with regularization obtained by setting $\beta = 0.2$. Using regularization while deblurring not only improves sharpness but also reduces noise. Table 2 shows the noise standard deviation computed on a small region at the extreme left of the curves in Figure

6 (c,d). Conventional deblurring algorithms such as Richardson-Lucy deconvolution do not use explicit regularization functions and hence are comparable to deblurring with $\beta = 0$. The improvement in sharpness due to the deblurring procedure is quantified in Table 1 by measuring the 95% to 5% drop-off width of the curves in Figure 6 (d). The sharpness improvement is also easier to visualize by studying Figure 7 that zooms into the step-transition region of Figure 6 (d).

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REFERENCES

- [1] Hasegawa BH. Physics of medical x-ray imaging. 2nd ed. Medical Physics Pub Corp; 1990.
- [2] Nelder JA, Mead R. A simplex method for function minimization. The computer journal. 1965;7(4):308–313.
- [3] Bouman C, Sauer K. A generalized Gaussian image model for edge-preserving MAP estimation. IEEE Transactions on image processing. 1993;2(3):296–310.
- [4] Mohan KA. Design of 4D X-ray tomography experiments for reconstruction using regularized iterative algorithms. In: Developments in X-Ray Tomography XI. vol. 10391; 2017. p. 103910U.
- [5] Chong EK, Zak SH. An introduction to optimization. vol. 76. John Wiley & Sons; 2013.

X-RAY COMPUTED TOMOGRAPHY FOR MEASUREMENT OF ADDITIVELY MANUFACTURED METAL THREADED PARTS

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INTRODUCTION

Additive manufacturing (AM) technologies are rapidly expanding in industrial domains that were typically dominated by conventional manufacturing technologies [1]. For example, AM technologies are starting to be used to produce metal threaded products, including dental implants [2]. Threaded joints are extensively used in many industrial applications and account for approximately 50 % of all joints produced in mechanical systems [3]. In particular, they allow obtaining assembly characterized by high strength and high rigidity as well as easy disassembly for maintenance or recycling purposes [3]. X-ray computed tomography (CT) is an advanced measuring technique increasingly used for several industrial metrology applications [4]. For the application of screw threads measurements, CT is capable of overcoming the limitations of conventional measuring techniques (i.e. tactile and optical measuring systems) [5]. In particular, CT allows holistic non-destructive evaluations of both internal and external threads, even when they are included in fragile or deformable parts (e.g. polymeric parts) or they are characterized by high form errors and highly complex texture (e.g. AM parts). This work proposes a CT-based methodology for measuring the geometry and local form errors of a threaded AM part. Moreover, the paper investigates and discusses the accuracy of CT dimensional measurement results.

MATERIALS AND METHODS

Components and instrumentation

Two components with different form errors and different texture were analysed and compared. The first one (Sample 1) is a calibrated thread gauge with standard thread geometry (UNC 5/16"-18) and very low form errors. The second component (Sample 2), shown in Fig. 1, is a dental implant made of Ti6Al4V, produced by direct metal laser sintering (DMLS). It is characterized by: (i) an external thread with non-standard geometry, very high form errors and

highly complex surface texture, and (ii) by a standard internal thread produced via micro-drilling and threading process [6].

Both components were scanned by means of a metrological CT system (Nikon Metrology MCT225) characterized by a micro-focus X-ray source, 16 bit detector with 2000×2000 pixel grid, high-precision linear guideways and cabinet with temperature controlled at 20 °C. The maximum permissible error (MPE) for length measurements is equal to $9 \pm (L/50) \mu\text{m}$, with measured length L expressed in millimetres.

CT data were elaborated by means of the analysis and visualization software VGStudio MAX 3.1 (Volume Graphics GmbH) and by a newly developed Matlab (MathWorks) routine.

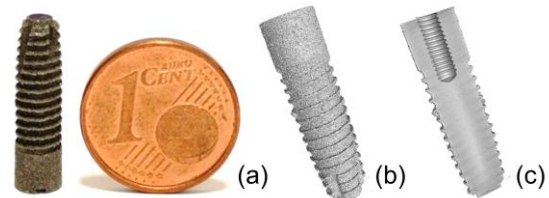


FIGURE 1. (a) Dental implant produced by DMLS of Ti6Al4V; (b) CT three-dimensional reconstruction of the part; (c) virtual sectioning of the CT scanned volume.

Methodology for thread measurement

The proposed methodology, followed for both the investigated samples, consists in 7 main steps:

1. Acquisition of X-ray projection images using the parameters listed in Table 1 (the parameters used for the two samples were kept as similar as possible in order to have comparable scanning conditions);
2. CT reconstruction of the 3D model of the scanned part;
3. Surface determination using the local adaptive thresholding algorithm available in VGStudio MAX 3.1.
4. Registration of the part with respect to the axis of the least-squares cylinder fitted to the external diameter;

5. Extraction of high-density point-cloud (see Fig. 2);
6. Extraction of points belonging to n radial profiles (using the newly developed Matlab routine; see Fig. 3), in order to analyse $n/2$ different radial cross-sections of the part. In this work n is equal to 360 (i.e. one profile for each rotational degree);
7. Measurement of the thread parameters of interest (described later) for each single considered cross-section.

TABLE 1. CT scanning parameters used for the calibrated thread gauge (Sample 1) and for the dental implant (Sample 2).

Parameter	Sample 1	Sample 2
Voltage	200 kV	200 kV
Current	34 μ A	34 μ A
Exposure	4000 ms	2000 ms
Nr. of projs	2000	2000
Filter	Cu; 0.5 mm	Cu; 0.25 mm
Voxel size	7.4 μ m	7.4 μ m

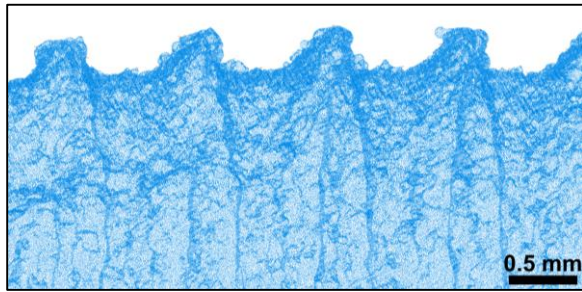


FIGURE 2. Portion of the high-density point cloud extracted from the surface of the CT reconstructed volume of Sample 2.

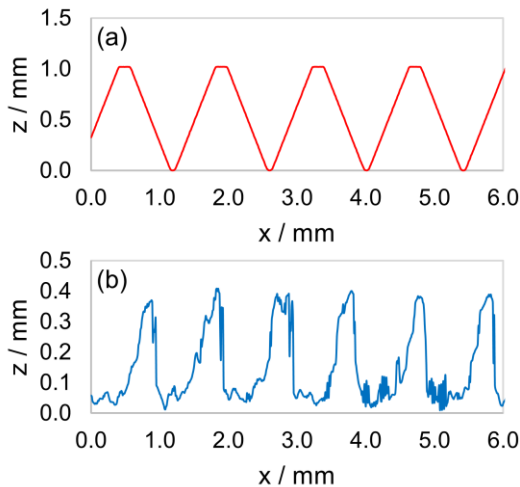


FIGURE 3. One of the 360 radial profiles extracted from the point cloud of (a) Sample 1 and (b) Sample 2.

The thread parameters of interest for this work are defined in the following and schematically illustrated in Fig. 4 for an external thread, according to ISO 5408:2009 [6]:

Minor diameter (d_{min})

Diameter of an imaginary cylinder tangent to the roots of an external thread and/or the crests of an internal thread.

Major diameter (d_{max})

Diameter of an imaginary cylinder tangent to the crests of an external thread and/or the roots of an internal thread.

Pitch (p)

Axial distance between two intersections formed by the pitch line intersecting a thread flank and the immediately adjacent and corresponding flank.

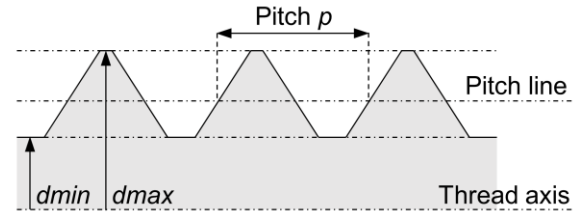


FIGURE 4. Schematic representation of major diameter (d_{max}), minor diameter (d_{min}) and pitch for an external thread. The thread axis and the pitch line are illustrated.

Systematic errors and uncertainty evaluation

The systematic errors and the uncertainty of CT measurements conducted in this work were determined by applying the substitution approach, according to the German guideline VDI/VDE 2630-2.1 [7], which adapts to CT the procedures that ISO 15530-3 [8] describes for tactile coordinate measuring machines (CMMs). This approach requires repeated measurements of a component calibrated with low uncertainty, similar to the actual components (with similarity conditions as reported in [7]).

The systematic error b is calculated as:

$$b = \bar{y} - y_{cal} \quad (\text{Eq.1})$$

where $\bar{y}$ is the average of n repeated measurements and y_{cal} is the calibrated value, commonly reported in the calibration certificate together with the calibration uncertainty.

The measurement result should be corrected for the systematic error and expressed as:

$$Y = y - b \pm U \quad (\text{Eq.2})$$

where Y is the corrected measured value, y the uncorrected measured value and U the expanded measurement uncertainty, determined as:

$$U = k \cdot \sqrt{u_{cal}^2 + u_{drift}^2 + u_p^2 + u_w^2 + u_b^2} \quad (\text{Eq.3})$$

where k is the coverage factor (for obtaining an expanded uncertainty at 95 % confidence interval), u_{cal} is the standard uncertainty of the calibrated values reported in the calibration certificate, u_{drift} is the uncertainty contribution of possible changes in the workpiece shape since the calibration referred to, u_p is measured as the standard deviation of the repeated measurements, u_w is the standard uncertainty related to variations in materials and production and u_b is the standard uncertainty associated to the correction of the bias b .

RESULTS

Fig. 5 shows the CT measurements results of d_{min} (Fig. 5.a), d_{max} (Fig. 5.b) and p (Fig. 5.c) for both Sample 1 and Sample 2, plotted as difference between measured and mean values in order to enable a better comparison.

It can be observed that the variability considering 180 different cross-sections is far lower for Sample 1 than for Sample 2. For Sample 1, the range is below $3.1 \mu\text{m}$ for both d_{max} and d_{min} and equal to $3.8 \mu\text{m}$ for p ; for Sample 2 the range is around $57 \mu\text{m}$ for both d_{max} and d_{min} and $183 \mu\text{m}$ for p . Such variability is due to the very different form errors and surface texture of the two analysed samples.

The mean systematic errors measured with the equation (Eq.1) for Sample 1 regarding d_{min} , d_{max} and p are equal to $-1.7 \mu\text{m}$, $-1.2 \mu\text{m}$ and $-0.5 \mu\text{m}$, respectively. Such errors were used to correct the measurement results (see equation (Eq.2)).

The expanded measurement uncertainty (95 % confidence level) related to Sample 1 was determined using equation (Eq.3). The uncertainty contribution u_w was approximated to zero in this case because the calibrated part coincides with the measured part. Supposing that no changes in the workpiece shape occurred in the time lapse from the calibration to the measurement, u_{drift} was approximated to zero as well. According to the guideline [7], u_b should contain the uncertainty of the thermal expansion coefficient (u_α):

$$u_b = (t_m - t_t) \cdot u_\alpha \cdot L \quad (\text{Eq.4})$$

where t_m is the average temperature of the measured sample, t_t the target metrological temperature equal to 20°C and L the measured length. It was determined below $0.01 \mu\text{m}$ for all the investigated thread parameters. The contribution u_p was measured from the standard deviation of 10 repeated measurements, multiplied for a safety factor equal to 1.2. It was

found to be $0.5 \mu\text{m}$ for d_{min} and d_{max} and below $0.1 \mu\text{m}$ for p . Finally, according to the thread gauge calibration certificate, u_{cal} is $1.5 \mu\text{m}$ for d_{min} and d_{max} and $1.0 \mu\text{m}$ for p .

The determined final expanded measurement uncertainties are reported in Table 2. Fig. 6 compares the measured values with the calibrated values. Uncertainty values are reported as well.

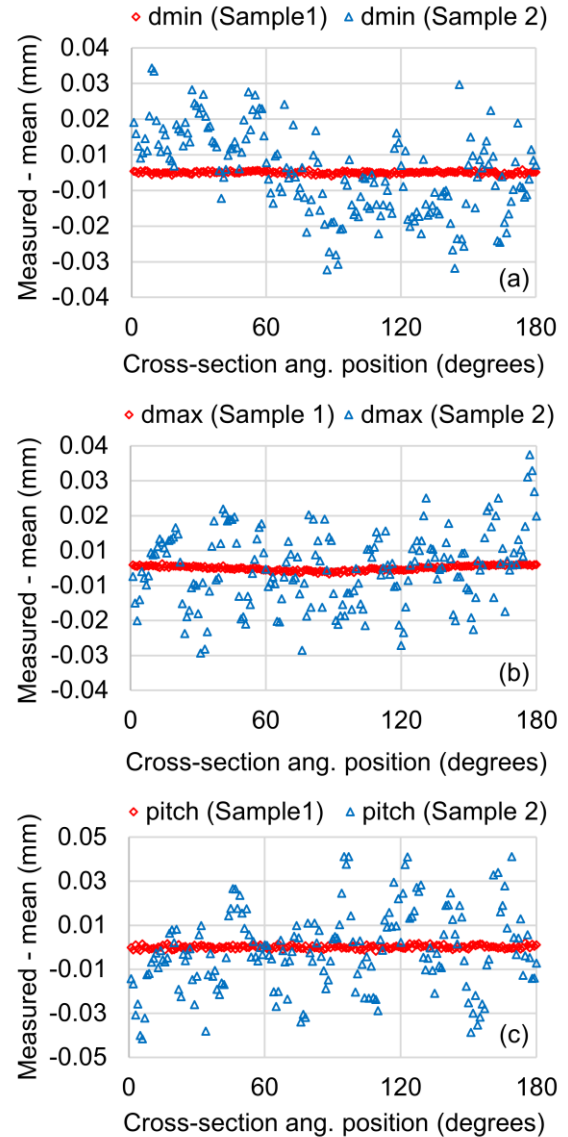


FIGURE 5. CT measurement of (a) minor diameter d_{min} , (b) major diameter d_{max} and (c) pitch p for Sample 1 and Sample 2, plotted as difference between measured and mean values. 180 cross-sections are considered (i.e. 360 radial profiles).

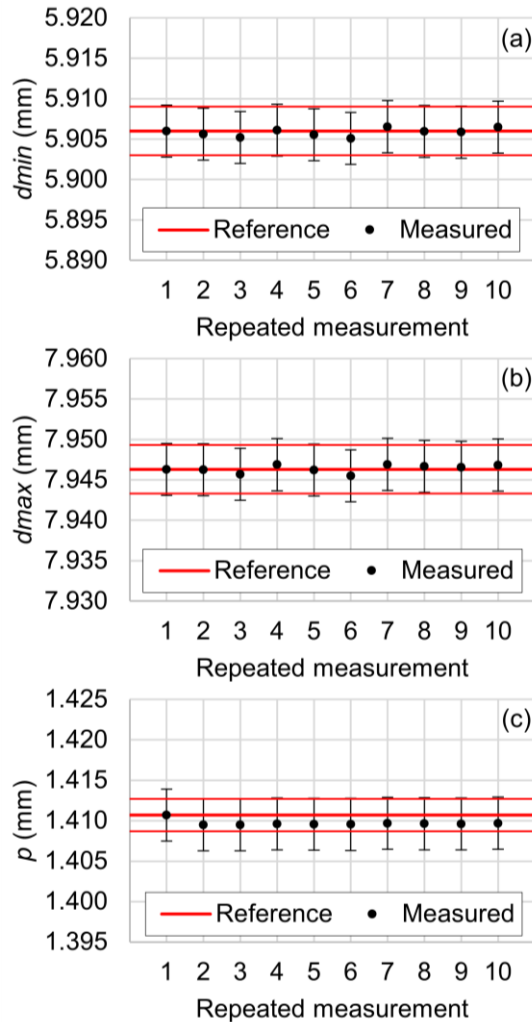


FIGURE 6. Comparison of 10 repeated measured values (black dots) with the corresponding calibrated/reference values (red line) for (a) d_{min} , (b) d_{max} and (c) p of Sample 1. Errors bars represent $\pm$ the expanded uncertainties of both measured and calibrated values.

Concerning the AM part (Sample 2), additional uncertainty contributions were considered in the uncertainty calculation to take into account the differences with respect to Sample 1, in terms of material, form and surface texture. In particular, to cope with the high form errors and surface roughness (see Fig. 3.b), the profiles extracted from the scan of Sample 1 were filtered using a smoothing filter, before applying the algorithm employed to measure the thread parameters. The uncertainty contribution to be associated to the combined effect of smoothing filter, surface texture and form errors was evaluated considering the distance between the measured point on the smoothed profile and the point which

should be measured on the real surface as average between the roughness steepest peak and deepest valley (i.e. P_z , [9]). This difference was locally evaluated on crests for d_{max} , on roots for d_{min} and on flanks for p . The final expanded measurement uncertainties are reported in Table 2.

TABLE 2. Expanded uncertainties (95 % confidence interval) measured for d_{min} , d_{max} and p for both Sample 1 and Sample 2.

Exp. Uncertainty	Sample 1	Sample 2
d_{min}	3.2 μm	138.0 μm
d_{max}	3.2 μm	70.1 μm
p	2.0 μm	22.7 μm

CONCLUSIONS

In this work, a CT-based methodology to measure the geometry and local form errors of a threaded AM part is proposed. The errors and uncertainty of such measurements were determined by comparison to a calibrated component with standard threaded geometry. Results demonstrated the capabilities of CT in performing a local evaluation of both thread dimensions and form errors, for AM threaded parts with high form errors and complex texture.

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The contribution of Mr R. Fioranzato to the experimental work is gratefully acknowledged.

REFERENCES

- [1] Schmidt M et al. 2017. Laser based additive manufacturing in industry and academia. *CIRP Annals*, 66(2), 561-583.
- [2] Traini T et al. (2008). Direct laser metal sintering as a new approach to fabrication of an isoelastic functionally graded material for manufacture of porous titanium dental implants. *Dental materials*, 24(11).
- [3] Hong E, Kats R. 2012. Non-contact inspection of internal threads of machined parts. *Int J Adv Manuf Technol*, 62:221-229
- [4] Carmignato S, Dewulf W, Leach R K (2018). *Industrial X-ray Computed Tomography*. Springer. DOI: 10.1007/978-3-319-59573-3.
- [5] Carmignato S, De Chiffre L (2003). A new method for thread calibration on coordinate measuring machines. *CIRP Annals*, 52/1:447-450. DOI: 10.1016/S0007-8506(07)60622-2.
- [6] Rysava Z, et al. (2016). Micro-drilling and Threading of the Ti6Al4 v Titanium Alloy Produced through Additive Manufacturing. *Procedia CIRP*, 46:583-586.

- [7] ISO 15530-3:2011, GPS – coordinate measuring machines (CMM): technique for determining the uncertainty of measurement – Part 3: use of calibrated workpieces or standards, ISO.
- [8] VDI/VDE 2630 - 2.1:2015 - CT in dimensional measurement – Determination of the uncertainty of measurement and the test process suitability of coordinate measurement systems with CT sensors.
- [9] ISO 5408:2009 - Screw threads – Vocabulary.
- [10] ISO 4288:1996 GPS – Surface Texture: Profile method – rules and procedures for the assessment of surface texture.

MEASUREMENT OF ADDITIVELY MANUFACTURED SURFACES WITH RE-ENTRANT FEATURES BY X-RAY COMPUTED TOMOGRAPHY

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INTRODUCTION

Components produced by additive manufacturing (AM) technologies are typically characterized by complex surface topographies, including the presence of micro-scale and freeform-shaped re-entrant features [1]. Such surfaces can be external or internal. The most commonly used techniques for topography measurements (i.e. contact probing and optical techniques) cannot access and measure neither internal surfaces nor re-entrant surface features [2]. X-ray computed tomography (CT) has recently started to be used as a viable alternative technique capable of obtaining topographical measurements of AM surfaces at micro-scale [3]. However, the most commonly used texture parameters –defined in ISO 4287 [4] for profile measurements and in ISO 25178-2 [5] for areal measurements– are not designed for taking into account complex re-entrant features [6]. This work proposes a new generalized definition for a selection of profile texture parameters, suited to characterize complex AM surface profiles including re-entrant features measured by CT. Such parameters were used to evaluate the accuracy of CT topography measurements of AM surface profiles in comparison to reference measurements.

MATERIALS AND METHODS

Generalization of profile texture parameters

The proposed generalization of profile texture parameters [7] is based on the parametrization of the profile containing re-entrant features, conducted by computing the infinitesimal arc length elements of consecutive segments along the investigated profile. In this work, the

parameters are measured on the primary profile (P-parameters [4]) after removing the form profile. The selected parameters are: Pa , Pq , Pp , Pv , Pz , Ps_k and Pku . The redefined texture profile parameters (measured on profiles containing re-entrant features) are compared with the analogous conventional parameters (measured on profiles after removal of re-entrant features). In the following, the proposed definition of Pa (taken as an example) is described.

Let the measured profile represented by a parametric curve $\mathbf{r}(t)$, the corresponding primary profile $\mathbf{r}_{res}(t)$ can be computed after removing the form profile $\mathbf{r}_F(t)$ (e.g. mean line), according to the following expression:

$$\mathbf{r}_{res}(t) = \mathbf{r}(t) - \mathbf{r}_F(t) \quad (\text{Eq. 1})$$

In other terms, the primary profile $\mathbf{r}_{res}(t)$ can be described as difference between the measured and the form profile. For simplicity, the following equation is introduced:

$$r_{res}(t) = \mathbf{r}_{res}(t) \cdot \mathbf{n}_F(t) \quad (\text{Eq. 2})$$

where $\mathbf{n}_F(t)$ is the normal vector of the form profile. The height parameters (e.g. Pa) can be calculated as the integral of a scalar field on the reference profile. For a complete description on the integration of scalar field on parametric curves see do Carmo [8]. The arithmetical mean deviation (Pa) of the assessed profile can be computed as:

$$Pa = \frac{1}{L_F} \int_{r(t)} |r_{res}(t)| dl \quad (\text{Eq. 3})$$

where $dl = \|\mathbf{r}'_F(t)\| dt$ is the infinitesimal arc length element and $L_F = \int_{r(t)} dl$ is the length of the measured profile projected on the reference one.

Reference measurements

As already stated in the introductory section, the most commonly used techniques for topography measurements (i.e. contact probing and optical techniques) are not able to measure re-entrant surface features. Consequently, they cannot be used to obtain reference measurements of the actual cross-sectional surface profiles of AM surfaces. In this work, the methodology proposed by Zanini et al. [2] was adopted to measure cross-sectional profiles (reference profiles) including re-entrant features, hence representative of the actual surface morphology. In particular, such methodology (schematically illustrated in Figure 1) consists in cutting and polishing an AM part. The resulting cross-section can then be imaged using an imaging probing system and the coordinates of points belonging to the profile of interest can be measured. In this work, a multisensor coordinate measuring machine (CMM) equipped with imaging probing sensor (Werth Video-Check IP 400) was used; the CMM has a maximum permissible error (MPE) for length measurements equal to $1.8 \pm (L/250) \mu\text{m}$ (with measured length L expressed in mm).

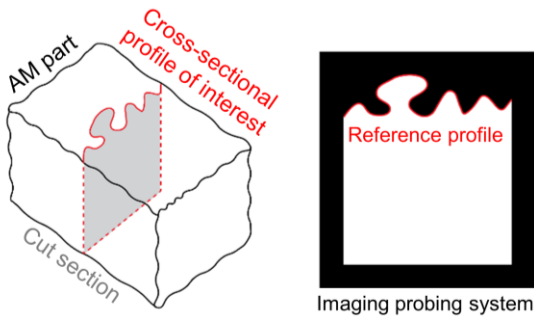


FIGURE 1. Schematic representation of an additive manufacturing component where a cross-sectional profile is highlighted in red (left); the actual profile including the re-entrant features can be acquired by using an imaging probing system after cutting and polishing one face of the sample (right).

Experimental methodology

The CT measurements discussed in this work were performed using a metrological CT system (Nikon Metrology MCT225), characterized by a micro-focus X-ray source (minimum focal spot size $3 \mu\text{m}$), 16 bit detector with 2000×2000 pixels, high-precision linear guideways, cabinet temperature controlled at 20°C and MPE for length measurements equal to $9 \pm (L/50) \mu\text{m}$ (with measured length L expressed in mm).

For assessing the accuracy of AM surface topography measurements performed by X-ray CT, the following 7 steps were followed:

- 1) Production of a sample by selective laser melting (SLM) of Ti6Al4V powder, using the design proposed by Zanini et al. [2];
- 2) CT scan of the sample (see Figure 2), using the scanning parameters reported in Table 1.
- 3) Cutting and polishing of one face on the sample, perpendicularly to the analysed surfaces, in order to allow imaging of 2D cross-sectional profiles (including re-entrant features);
- 4) Acquisition of 2D reference profiles;
- 5) CT scan of the cut sample using the same parameters (see Table 1);
- 6) Alignment of CT volume acquired before the cutting/polishing procedure with CT volume obtained after the cutting/polishing, to identify the same profiles measured by the imaging probing system.
- 7) Comparison of profiles acquired using CT with the reference profiles.

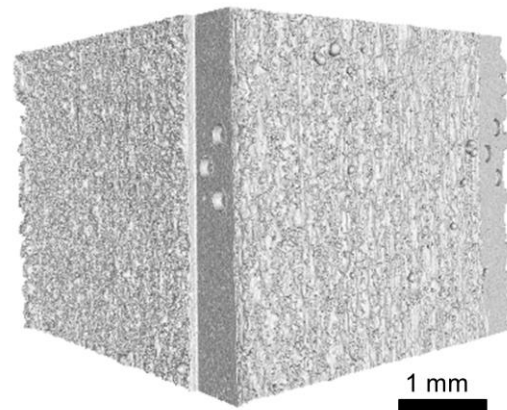


FIGURE 2. CT scanned volume of Ti6Al4V SLM reference sample.

TABLE 1. CT scanning parameters.

Parameter	Value
Voltage	190 kV
Current	$36 \mu\text{A}$
Exposure time	2000 ms
Nr. of projections	1800
Voxel size	4, 6, 8, 10, $12 \mu\text{m}$

RESULTS

Comparison of parameters

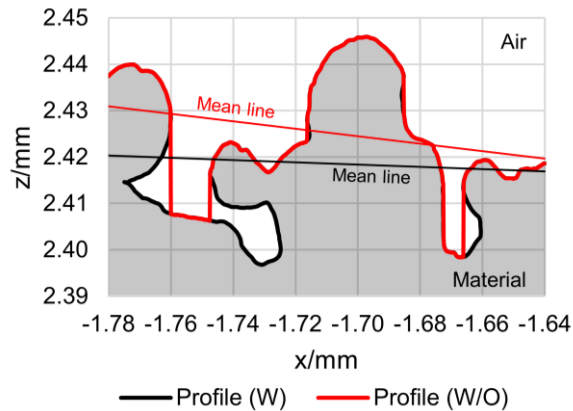


FIGURE 3. Portion of an actual profile measured using an imaging probing sensor (black profile) and the same profile after removing the re-entrant features (red profile). Mean lines are depicted.

In this paragraph, the generalized surface profile parameters will be compared with the analogous conventional parameters. The first ones are computed on the actual reference profiles (i.e. profiles including re-entrant surface features and parametrized as explained in the paragraph “Generalization of profile texture parameters”); the second ones are instead computed on the same profiles after removal of re-entrant surface features.

Figure 3 shows a portion of an actual profile obtained by the imaging probing system introduced in the paragraph “Experimental methodology”, taken as an example. The conventional profile parameters evaluated on the profile with no re-entrant features (red profile) were compared with the analogous generalized parameters measured on the actual profile (black line): the percentage differences are reported in Table 2. P_a , P_q , P_p and P_v calculation is based

on the mean line, which changes consistently from one profile to the other (see Figure 3). In the case of P_p , the percentage difference is high because the mean line is shifted towards the profile peaks after removing the re-entrant features. As regards P_v , the mean line is shifted farther from the profile valleys but the information on valleys can be missed when removing the re-entrant features as seen in Figure 3, hence reducing the resulting error. P_z is affected by the non-complete information about the valleys, as demonstrated by the 10 % difference. In the example, P_{ku} remains almost equal as no significant modification of the profile steepness occurs. On the contrary, P_{sk} is deeply affected by the different description of the valleys, which can change significantly the symmetry of the profile.

TABLE 2. Percentage differences between conventional and generalized profile texture parameters.

Parameter	Difference
P_a	6 %
P_q	7 %
P_p	22 %
P_v	4 %
P_z	10 %
P_{ku}	< 1 %
P_{sk}	> 100 %

Accuracy of CT measurements

The CT capability of measuring micro-scale topographical details (including re-entrant features) depends on the achieved metrological structural resolution [8]. The voxel size is one of the factors having the most significant influence on the metrological structural resolution. Moreover, in conventional cone-beam CT scanning, the magnification factor (m) is geometrically obtained by dividing the source-to-

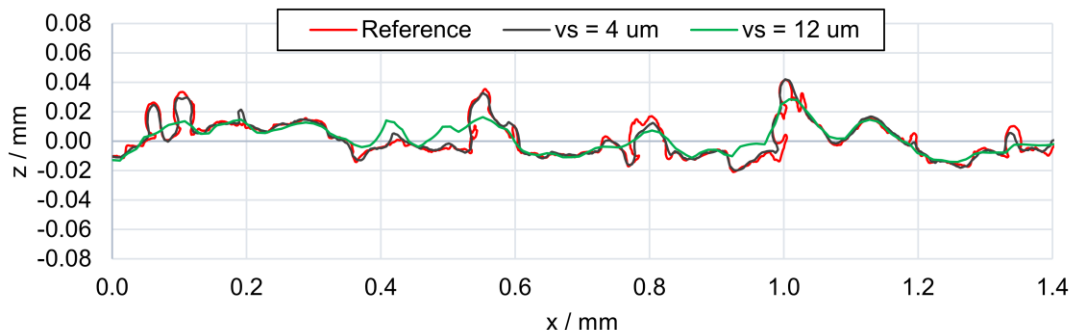


FIGURE 4. Portion of a cross-sectional profile measured by CT at the highest (black profile) and lowest magnification (green profile) compared with the reference profile (red profile).

detector distance (SDD) by the source-to-object distance (SOD). The closer the object is to the source, the higher is the geometrical magnification, hence the smaller is the resulting voxel size (v_s), according to the following relation:

$$v_s = p_s \cdot m = p_s \cdot (SDD/SOD) \quad (\text{Eq. 4})$$

where p_s is the detector pixel size.

It is clear that the object dimensions should be small enough in order to reach very small voxel sizes keeping, at the same time, the object within the detector field of view. Consequently, the maximum allowed dimension for the entire object (D_{max}) to be scanned depends on the voxel size (v_s) and the number of pixels on a detector row (n_p) of the detector, as described by the following equation:

$$D_{max} = v_s \cdot n_p = p_s \cdot (SDD/SOD) \cdot n_p \quad (\text{Eq. 5})$$

For the above-mentioned reasons, the effect of the voxel size is specifically addressed in this paper. In particular, the generalized profile parameters proposed in this work were computed on cross-sectional profiles measured by CT with 5 different voxel dimensions (see Table 1).

Figure 4 provides a visual comparison of one profile taken as an example measured by CT with the maximum and the minimum considered voxel sizes with the corresponding reference profile.

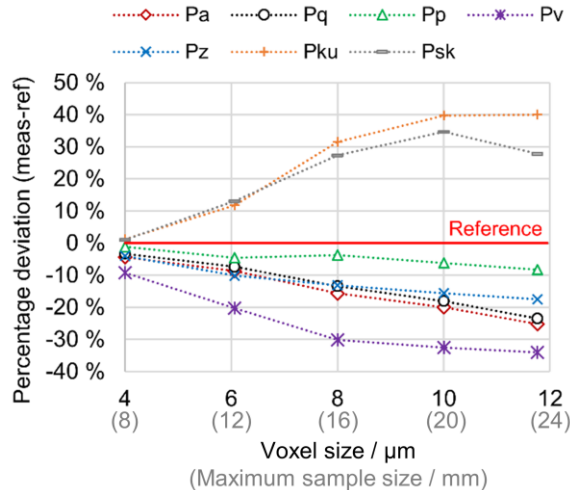


FIGURE 5. Deviations between profile parameters measured by CT with different voxel sizes and parameters measured on the corresponding reference profile. Maximum sample sizes are reported for a detector with a 2000×2000 grid of pixels with size of 0.2 mm.

The diagram reported in Figure 5 plots the percentage deviations obtained for each investigated parameter between the measured profiles and reference profile. Results show that

errors below 10 % were obtained for the majority of the investigated parameters with voxel size equal or lower than 6 μm (corresponding to a maximum sample size of approximately 12 mm for a detector with 2000×2000 grid of pixels with size equal to 0.2 mm).

CONCLUSIONS

The surface texture of Ti6Al4V SLM samples was investigated in this work using a new generalized definition of profile parameters, suited to characterize complex AM surface profiles, including re-entrant features, measured by CT. The relevance of such redefinition was proven by comparing conventional and generalized parameters on the same surface profiles. The new parameters were then computed on profiles measured by CT with different voxel sizes. The dependency between the voxel size and the considered profile texture parameters was observed. Errors below 10 % with respect to the reference measurements was obtained with voxel size equal or below 6 μm .

REFERENCES

- [1] Townsend A et al (2016). Surface texture metrology for metal additive manufacturing: a review. *Precision Engineering* 46 34-47
- [2] Zanini F et al (2018). Accuracy of surface topography measurements performed by X-ray computed tomography on additively manufactured metal parts. 18th euspen's international conference, Venice, Italy
- [3] Thompson A et al (2017). Topography of selectively laser melted surfaces: A comparison of different measurement methods. *CIRP Annals Man. Tech.* 66.
- [4] ISO 4288:1996 GPS—Surface Texture: Profile method—rules and procedures for the assessment of surface texture.
- [5] ISO 25178-2:2012 GPS—Surface Texture: Areal—Part 2: Terms, Definitions and Surface Texture Parameters.
- [6] Pagani L et al (2017). Towards a new definition of areal surface texture parameters on freeform surface. *Measurement*, 109, pp. 281-291
- [7] Pagani L et al (2018). Generalization of profile texture parameters for additively manufactured surfaces. XXII IMEKO World Congress, Belfast (UK)
- [8] Zanini F, Carmignato S (2017). Two-spheres method for evaluating the metrological structural resolution in dimensional computed tomography. *Meas. Sci. Technol.* doi.org/10.1088/1361-6501/aa85b7

SCANNING CHROMATIC CONFOCAL SENSOR FOR FAST 3D SURFACE CHARACTERIZATION

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ABSTRACT

This paper presents a scanning system with a chromatic confocal displacement sensor, using two types of actuators for fast 3-D surface characterization. For raster scanning of the sensor's optical spot over a sample, a linear stage as the first actuator moves the sample along the slow scanning axis. Because the relatively large moving mass of the sample can restrict the scanning speed of such an actuator, a galvanometer mirror is used for the fast scanning axis, reducing the inertia for the fast triangular motion. To accurately track the motion reference for high quality imaging, the galvanometer mirror is regulated by feedback control and modeling-free learning control. The resulting tracking error is only 1.2 mdeg_{rms} for 20 Hz triangular motion of 6 deg. The scanning motion is used to generate a 125×125 pixel image in 3.1 s, demonstrating the improvement of the imaging quality. A further advantage of the chromatic confocal sensor is confirmed by simultaneously imaging the topography and thickness of a glass substrate.

INTRODUCTION

Surface conditions of 3-D printed parts can influence their functionality [1], and surface characterization is indispensable to analyze and improve the production quality. Particularly when the quality is improved by inline metrology [2], a compact sensor system for surface characterization is desired, which has high resolution and is able to achieve a high frame rate of 3-D images.

For surface characterization with high accuracy and resolution, high-precision optical displacement sensors can be used to laterally scan the surface. An advantage of those sensors is that surfaces can be inspected without contact in order to prevent damage, unlike stylus profilers for example [3]. Among different types of optical methods, laser triangulation has been used to measure surface topography for three decades, achieving high accuracy and resolution [4]. A monochromatic confocal displacement sen-

sor enables to inspect surface topography, as well as the thickness of transparent layers [5]. However, the focal point of the beam needs to scan vertically to the sample, for example by using a varifocal lens, which can restrict the vertical resolution and the frame rate of 3-D imaging [6]. Chromatic confocal displacement sensors solve this problem by using chromatic aberration and able to simultaneously acquire topography and thickness information without the vertical scanning motion [7].

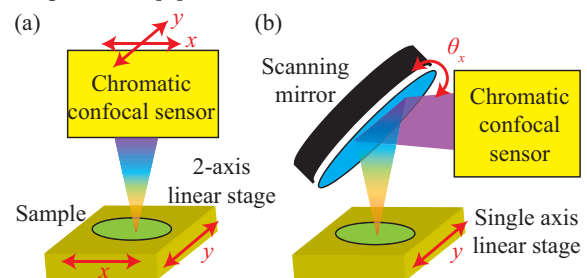


FIGURE 1. Scanning system with a chromatic confocal displacement sensor for surface topography imaging: (a) system moving the sample or the sensor, and (b) system with a scanning mirror for the fast scanning x axis.

Lateral scanning motion of the optical displacement sensor can limit the achievable performance. When the sensor or sample is moved by a linear stage or motor [8], as shown in Fig. 1(a), the mover can be relatively heavy with low-frequency mechanical resonances, which restrict the control bandwidth [9] and results in a long imaging time. Furthermore, when the sensor is moved, an additional concern is slippage of its components due to the high acceleration forces of the scanning motion. These problems are solved by scanning the optical path, instead of the sensor or sample, so that the mover inertia is decreased for high control bandwidth, as shown in Fig. 1(b). For this purpose, galvanometer mirrors or fast steering mirrors have been integrated in optical scanning laser triangulation sensor systems [4, 10].

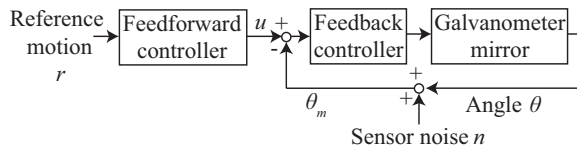


FIGURE 3. Control block diagram of the galvanometer mirror, where u is the input to the stabilized galvanometer mirror and θ_m is the angular sensor output.

When the open-loop cross-over frequency is too low, it is difficult to guarantee closed-loop stability. This is because the nonlinear dynamics of the bearing friction [14] change the frequency response at low frequencies. For example at the turning points of the triangular motion, the mirror's rotational speed is zero, resulting in static friction. Consequently, the open-loop cross-over frequency has to be set to a sufficiently high frequency where the friction does not influence the system dynamics for closed-loop stability. In contrast, the higher the open-loop cross-over is, the more the controller feeds back sensor noise n to the system (Fig. 3), impairing the motion precision [15]. In order to achieve a high precision of motion, the open-loop cross-over frequency is minimized within a range guaranteeing closed-loop stability.

For validation, the complementary sensitivity function, which is the transfer function from u to θ_m in Fig. 3, is measured and shown in Fig. 4. Due to the low open-loop cross-over frequency, the -3 dB control bandwidth is only 303 Hz, which is beneficial to achieve high precision against the sensor noise.

Feedforward control

While the low control bandwidth is desired for high precision, it is problematic for accurately tracking the reference motion. To improve the accuracy, feedforward control may be used, such that the signal u can be generated from the noise-free motion reference r (Fig. 3). Feedforward control design typically requires an accurate model [16]. However, it is time-consuming to derive an accurate model, due to the friction's nonlinear dynamics [14]. Furthermore, a friction model may vary, dependent on temperature [17]. To overcome these problems, modeling-free inversion-based iterative control (IIC) [18] is used as a feedforward controller for the galvanometer mirror.

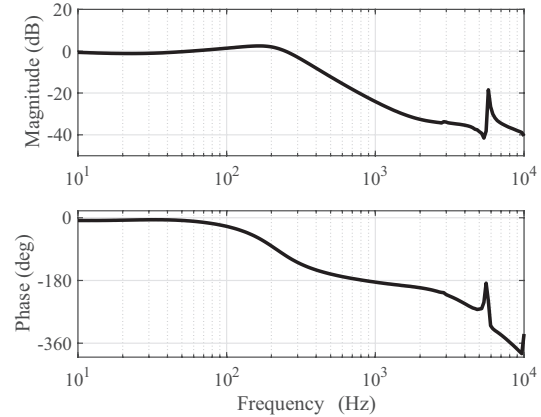


FIGURE 4. Measured complementary sensitivity function for the validation of the feedback control design.

Modeling-free IIC iteratively corrects the control input by learning from the measured tracking error of the previous trial such that it decreases in the next trial. Unlike other types of learning algorithms (e.g. iterative learning control [19]), modeling-free IIC corrects the control input at selected frequencies only. For the triangular motion, the correction frequencies are set to its fundamental and harmonic frequencies. This is beneficial as it filters the angular sensor noise between the harmonic frequencies for high-precision motion. Furthermore, modeling-free IIC performs system identification in each trial, for example by a quasi-Newton method. In this paper, the Secant method [20] is selected for fast and accurate learning, and modeling-free IIC is implemented as presented in [20].

Fig. 5 shows experimental results with the 20 Hz triangular motion reference. In the 0th trial, the galvanometer mirror is controlled only by the feedback controller for the system identification of the modeling-free IIC. In Fig. 5(a), the tracking error is 152 mdeg_{rms} with the feedback controller in the 0th iteration. The modeling-free IIC quickly compensates the majority of this large tracking error within the first three trials. Eventually in the 20th trial, the modeling-free IIC decreases the tracking error by a factor of 126 to 1.2 mdeg_{rms}. Fig. 5(b) and (c) show the reference r with the measured angle θ_m and the tracking error ($r - \theta_m$) of the 20th trial, respectively. The tracking error shows no periodic components that are synchronized to r , which demonstrates a highly accurate motion of the galvanometer mirror.

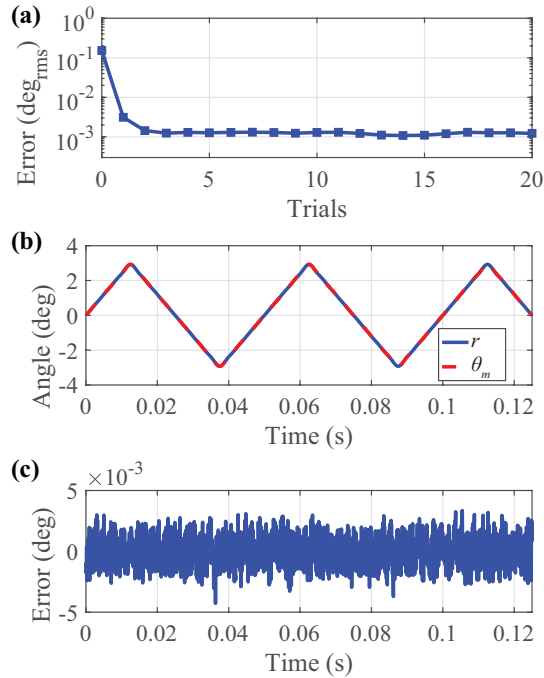


FIGURE 5. Triangular motion of the galvanometer mirror with the modeling-free IIC: (a) learning transient, as well as (b) the reference motion r with the measured angle θ_m and (c) the tracking error $r - \theta_m$ of the 20th trial.

3-D IMAGING

The accurate and precise motion of the galvanometer mirror in the previous section is used to scan a sample surface for 3-D imaging. For the experiments, the confocal sensor measures the displacement and thickness at 5 kHz. With this setting and the galvanometer mirror's motion, it takes 3.1 s to generate an image of 125×125 pixels. Fig. 6 shows Nanoblocks (Kawada, Tokyo, Japan) and a glass substrate with a thickness of 1 mm, which are used as samples. The cylindrical shape of the blocks has a diameter and height of 2.5 mm and 1.7 mm, respectively.

The image in Fig. 7(a) is obtained when the galvanometer mirror is regulated by the feedback controller only. Horizontal stripes are visible around the edges of the features due to the tracking error of the galvanometer mirror. However, they are successfully removed by modeling-free IIC, as shown in Fig. 7(b). It demonstrates that the accurate and precise galvanometer mirror's motion improves the imaging quality. In the next experiment, a corner of the glass sub-

strate is imaged. The results are shown in Fig. 8 and demonstrate that the surface topography and the glass thickness are simultaneously imaged in 3.1 s. Overall, the experiments clearly show the benefits of scanning the optical path for fast 3-D imaging, as well as the capability of the chromatic confocal sensor to measure the topography and the thickness of a transparent material at the same time.

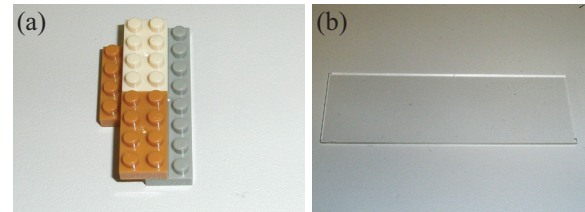


FIGURE 6. Photograph of samples: (a) Nanoblock and (b) glass substrate.

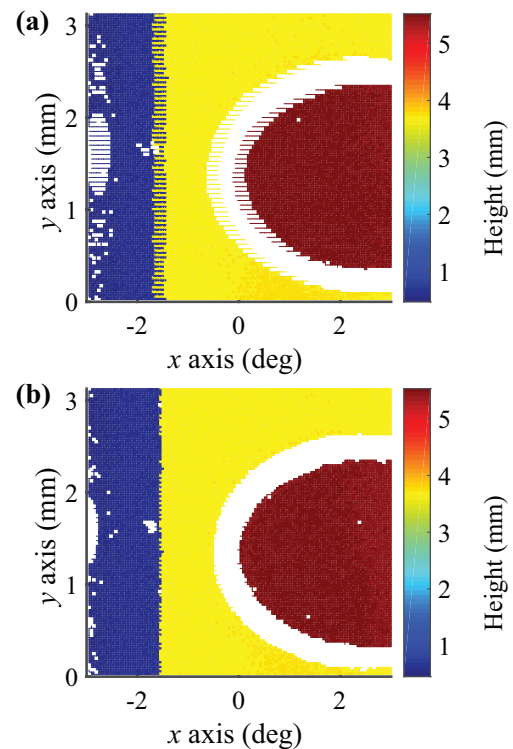


FIGURE 7. Measured images of a block topography when the galvanometer mirror is regulated by the feedback controller (a) without and (b) with the modeling-free IIC.

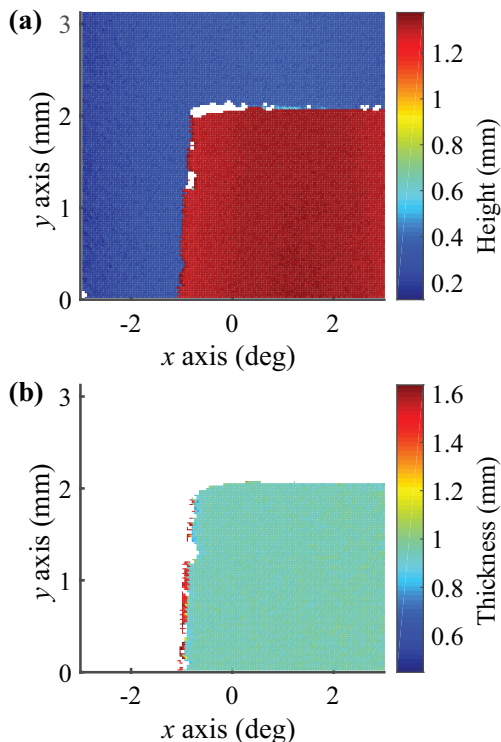


FIGURE 8. Imaged glass substrate's corner: (a) topography and (b) thickness.

CONCLUSION AND FUTURE WORK

For fast 3-D surface characterization with a chromatic confocal sensor, this paper presents a scanning system where a galvanometer mirror redirects the optical spot without laterally moving mechanical components along the fast scanning axis. To realize an accurate and precise scanning motion, feedback control and modeling-free IIC are designed for the galvanometer mirror. Its effectiveness is verified by imaging a glass substrate as well as Nanoblocks having cylinders with a diameter of 2.5 mm. In the future, the resolution and speed of 3-D imaging will be improved by increasing the measurement rate of the chromatic confocal sensor and the scanning frequency of the galvanometer mirror.

ACKNOWLEDGMENT

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REFERENCES

- [1] Garcia CR, Rumpf RC, Tsang HH, Barton JH. Effects of extreme surface roughness on 3D printed horn antenna. *Electronics Letters*. 2013 June;49(12):734–736.
- [2] Schmitt R, Moenning F. Ensure success with inline-metrology. In: *IMEKO XVIII World Congress*; 2006. .
- [3] Lee DH, Cho NG. Assessment of surface profile data acquired by a stylus profilometer. *Measurement Science and Technology*. 2012;23(10):105601.
- [4] Blais F. Review of 20 years of range sensor development. *Journal of Electronic Imaging*. 2004;13:231–240.
- [5] Weng CJ, Lu BR, Cheng PY, Hwang CH, Chen CY. Measuring the thickness of transparent objects using a confocal displacement sensor. In: *IEEE International Instrumentation and Measurement Technology Conference*; 2017. p. 1–5.
- [6] Meinert T, Weber N, Zappe H, Seifert A. Varifocal MOEMS fiber scanner for confocal endomicroscopy. *Opt Express*. 2014 Dec;22(25):31529–31544.
- [7] Jordan HJ. Optical chromatic confocal probes. In: *XII International Colloquium on Surfaces*; 2008. p. 200–209.
- [8] Tomlinson K, Seagle CT, Huang H, Smith GE, Taylor JL, Paguio RR. Enhanced Dual Confocal Measurement System. *Fusion Science and Technology*. 2018;73(2):139–148.
- [9] Ito S, Steininger J, Schitter G. Low-stiffness dual stage actuator for long range positioning with nanometer resolution. *Mechatronics*. 2015;29:46–56.
- [10] Schlarp J, Csencsics E, Schitter G. Optical scanning of laser line sensors for 3D imaging. *Applied Optics*. 2018;57(20).
- [11] Noda K, Binh-Khiem N, Takei Y, Takahata T, Matsumoto K, Shimoyama I. Multi-axial confocal distance sensor using varifocal liquid lens. In: *2013 Transducers Eurosensors XXVII: The 17th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS EUROSENSORS XXVII)*; 2013. p. 1499–1502.

- [12] Yoo HW, Ito S, Schitter G. High speed laser scanning microscopy by iterative learning control of a galvanometer scanner. *Control Engineering Practice*. 2016;50:12–21.
- [13] Ito S, Unger S, Schitter G. Vibration isolator carrying atomic force microscope's head. *Mechatronics*. 2017;44:32–41.
- [14] Johansson K, Canudas-de Wit C. Revisiting the LuGre friction model. *IEEE Control Systems Magazine*. 2008 Dec;28(6):101–114.
- [15] Van de Vegte J. *Feedback Control Systems*. Prentice Hall; 1994.
- [16] Leang KK, Zou Q, Devasia S. Feedforward control of piezoactuators in atomic force microscope systems. *IEEE Control Systems Magazine*. 2009 Feb;29(1):70–82.
- [17] Choo JH, Glovnea RP, Forrest AK, Spikes HA. A low friction bearing based on liquid slip at the wall. *ASME Journal of Tribology*. 2007;129(3):611–620.
- [18] Li Y, Bechhoefer J. Model-free iterative control of repetitive dynamics for high-speed scanning in atomic force microscopy. *Review of Scientific Instruments*. 2009;80(1):013702.
- [19] Bristow DA, Tharayil M, Alleyne AG. A survey of iterative learning control. *IEEE Control Systems Magazine*. 2006 June;26(3):96–114.
- [20] Ito S, Yoo HW, Schitter G. Comparison of modeling-free learning control algorithms for galvanometer scanner's periodic motion. In: *IEEE International Conference on Advanced Intelligent Mechatronics*; 2017. p. 1357–1362.

FOCUS VARIATION MEASUREMENT OF METAL ADDITIVELY MANUFACTURED SURFACES

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INTRODUCTION

Metal additive manufactured (AM) surfaces produced via powder bed fusion (PBF) feature complex and irregular topographies and significant variations depending on build orientation [1–3]. Top surfaces contain traces of the laser or electron-beam melting scan path, as well as sparse spatter formations created during the processing of the layer. Side surfaces are the result of layer-upon-layer stacking and feature attached, partially melted or unmelted particles [3,4]. When measured with optical instruments, PBF surfaces present significant challenges related to disuniformity of optical properties, with highly reflective smooth regions appearing together with poorly contrasted, dark recesses, high aspect-ratio features, high slopes and undercuts [2,5]. Amongst optical surface topography measurement technologies, focus variation (FV) offers a good compromise between quality of measurement results, ease of operation and required measurement time [6,7]. Thus, FV has often been used for the measurement of metal AM surfaces [2,3,8–10]. Because of the widespread adoption of FV instruments for the measurement of metal AM surfaces, further research is required to improve our understanding of how the FV technology behaves when applied to such surfaces, with the final aim of identifying guidelines showing how FV instruments should be configured for optimal operation for AM. Similar research is being performed for coherence scanning interferometry [5] and other instruments. To ensure generality of the results, the experiments are performed on a variety of materials and metal powder bed fusion (PBF) processes. The measurements were performed using an Alicona InfiniteFocus (IF) G5 instrument, but the findings should apply to any standard FV instrument [11].

METHODOLOGY

Four samples were considered. Three were produced by laser powder bed fusion (LPBF, Renishaw AM250) and one by electron PBF (electron beam melting (EBM) Arcam A2X). Both the top and side (vertical) surfaces of the samples were considered for the analysis. For the material of the samples, Al-Si-10Mg, Inconel 718 and Ti-6Al-4V were used for LPBF, Ti-6Al-4V for EBM.

Measurement

The considered measurement process parameters were: magnification (10×, 20× and 50× objective lens); type of illumination (coaxial, polarised coaxial and ring light); desired, reference lateral resolution (a variable introduced by the instrument manufacturer that indirectly controls the lateral sampling distance [12] and ultimately affects the actual lateral resolution of the measurement); and vertical resolution (a variable that controls the vertical spacing between subsequent images taken during vertical scanning, where the images are then used to compute the local surface height values through detection of maximum contrast [7,8]). Lateral and vertical resolution levels were chosen by considering the default values suggested by the instrument control software at each magnification, plus one or two additional levels also chosen within the range of acceptable values suggested by the instrument software. From each one of the four samples, two regions were selected, one on the top surface, the other on one of the sides. Over each region, three replicate measurements were performed in sequence, under repeatability conditions (i.e. same set-up and position of the objective over the region), leading to a total of twenty-four measurement per set-up. A total of sixty-three set-ups were investigated, considering the combinations of measurement control parameters illustrated in Table 1, leading to a grand total of 1512 measured datasets.

TABLE 1. Selected FV measurement process parameters and their values

Objective lens magnification	10× (NA 0.3 FoV (1.62×1.62) mm)	20× (NA 0.4 FoV (0.81×0.81) mm)	50× (NA 0.6 FoV (0.32×0.32) mm)
Type of illumination	Coaxial Polarised coaxial Ring light	Coaxial Polarised coaxial Ring light	Coaxial Polarised coaxial Ring light
Lateral resolution / μm	2, 4	1, 2, 3	1, 2
Vertical resolution / nm	100, 300, 900	50, 200, 500	20, 50, 200

Measurement quality indicators

Each measurement performed with FV instrument results in a height map, an RGB colour map and a “quality” map (map of local repeatability error). The following were considered as quality indicators:

- the upper quartile (Q3) of the distribution of repeatability errors, as extracted from the quality map (as shown in Figure 1);
- the percentage of non-measured points in the height map (NMP); and
- the areal surface texture field parameter S_a (arithmetical mean height) from the standard ISO 25178-2 [13].

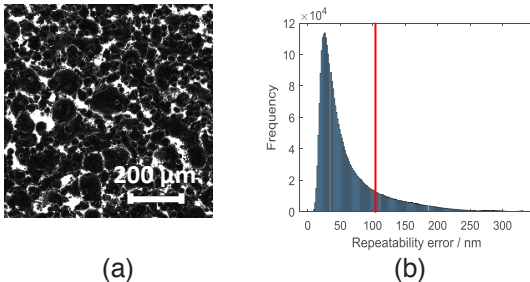


FIGURE 1. Computation of upper quartile of repeatability error (Q3); a) quality map from the measurement of one of the metal additive surfaces; b) probability distribution of repeatability error (upper quartile indicated in red)

Data generation and analysis

For each measurement region and for each magnification, three independent, general full factorial designs of experiments (DOE) were generated for Q3, NMP and S_a respectively, to determine the sensitivity of the quality indicators to the factors: type of illumination, vertical resolution and lateral resolution (with levels as previously illustrated in Table 1). From each DOE, regression models were fitted, and results were investigated by looking at the main effects plots and statistical significance through ANOVA.

RESULTS

Visual inspection

Visual inspection of the height maps and RGB maps was used to assess whether changing measurement control parameters would induce visually appreciable alterations in the reconstructed topographies.

The most evident result of observing at different magnifications is that a different range of topographic scales are captured: for the test cases, lower magnifications allowed capturing of a larger number of weld tracks, as well the underlying large-scale waviness often present on top surfaces [2]. Higher magnifications allowed the acquisition of smaller-scale features such as weld ripples [4]. Several surface features were visible at all magnifications (e.g. medium-sized spatter formations), albeit represented by slightly different topographic content in the spatial frequency domain. However, such differences were usually not clearly appreciable by simple visual assessment.

Changes in the vertical resolution also did not produce visually appreciable alterations in the reconstructed height maps.

On the contrary, changing lateral resolution produced a visible effect in the reconstructed height maps (Figure 2). Despite the size of the measured area remaining the same, improved lateral resolutions (smaller lateral resolution values) led to increased visibility of small-scale, topographic features. On the contrary, worse resolutions led to loss of small-scale detail, visually similar to applying a smoothing effect to the topography.

Changes of illumination type were primarily appreciable by looking at the RGB maps resulting from measurement (Figure 3). The RGB maps contain pixel information used to compute

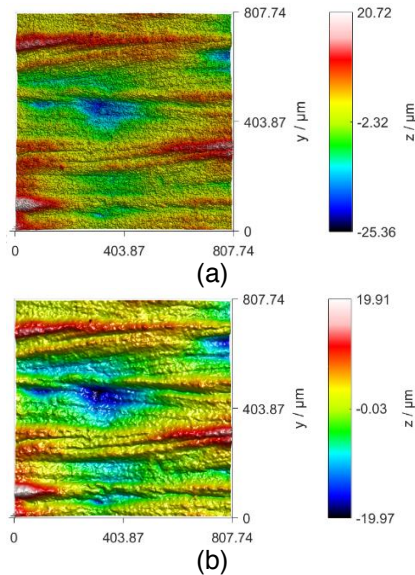


FIGURE 2. Effects of changing lateral resolution: height map visualisation of EBM titanium alloy top surface measured using 20× magnification, coaxial light, vertical resolution at 200 nm, and lateral resolution at (a) 1 μm and (b) 3 μm

maximum contrast by the FV technology during vertical scanning: it is, therefore, expected that changes in the RGB maps may also correspond to changes in the height maps. However, as shown in Figure 3, despite the RGB maps appearing different, a similar level of discrepancy was not equivalently visible on the associated height maps, albeit differences in height ranges

were undeniably present as shown by the height ranges reported in the associated colour bars.

Quality of model fitting

The determination coefficient (R^2) of the regression models for Q3 was above 80% in almost all cases, showing good fitting overall. On the contrary, the regression models for NMP were characterised by poor fitting so results could not be considered as particularly reliable. R^2 was above 85% in all cases for the models for the surface texture parameter S_a .

ANOVA and main effects plots

Vertical resolution: vertical resolution was always significant ($p < 0.05$) for Q3, with improved resolutions (smaller values) leading to lower Q3 values as shown in Figure 4. However, improved vertical resolutions (larger values) also led to higher NMP (Figure 5). From the ANOVA there was not enough evidence to confirm the influence of vertical resolution on S_a .

Lateral resolution: improved lateral resolutions (smaller values) generally led to higher NMP, whilst there was not enough evidence from the ANOVA to confirm the influence of lateral resolution on Q3. Worse lateral resolutions (larger values) also usually led to smaller S_a values, because of larger resolution values acting as a low-pass filter, i.e. introducing a smoothing effect in the reconstructed topography. In a few

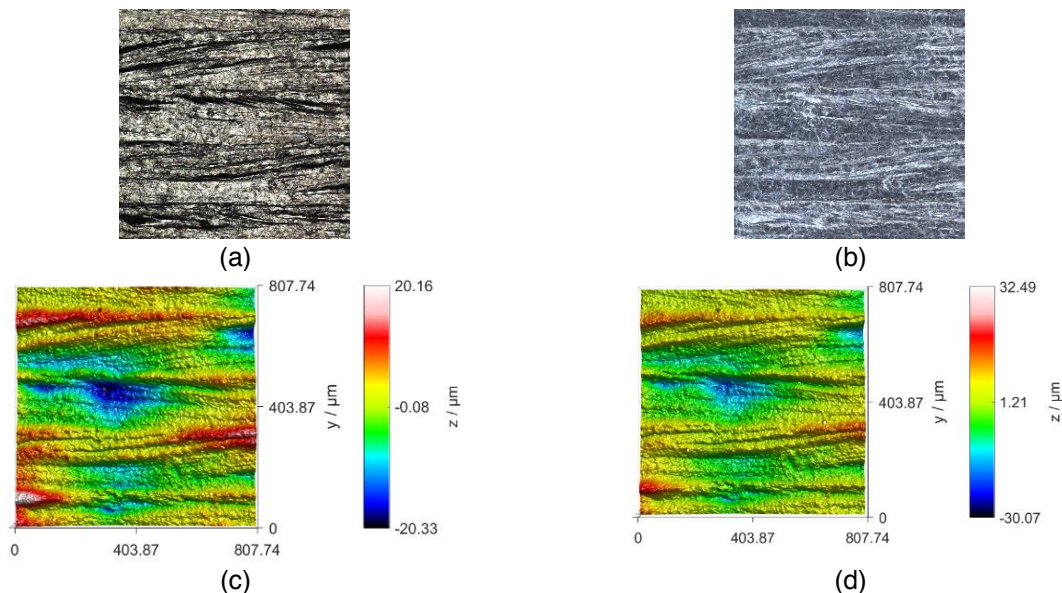


FIGURE 3. Effects of changing illumination type: EBM titanium alloy top surface measured using 20× magnification, lateral resolution at 2 μm, vertical resolution at 200 nm; focus stacked RGB images using (a) coaxial light and (b) ring light illumination. Corresponding height maps using (c) coaxial light and (d) ring light illumination.

cases (some side surfaces at higher magnifications), the trend was inverted, presumably because of S_a being influenced by individual features covering a higher percentage of the field of view.

Illumination type: The ANOVA was inconclusive regarding the effects of type of illumination on Q3 and NMP, except at 10 $\times$ magnification, where usually smoother surfaces (top surfaces) benefitted more from ring light illumination (lower NMP). The influence of type of illumination on the S_a parameter was consistently observed. Usually, ring light illumination led to lower S_a at lower magnifications (10 $\times$, 20 $\times$), as shown in Figure 6. A not-so-consistent trend was observed at 50 $\times$, possibly because of individual features occupying a significant percentage of the field of view.

DISCUSSION

Within this work, surface topographies ranging from smoother to rougher, from highly reflective to poorly reflective, and from low to high aspect-ratios were covered. It is, therefore, reasonable to assume that surfaces originating from different manufacturing processes, but ultimately similar in terms of topographic complexity and optical properties, may lead to similar behaviour of the FV technology.

The results presented in this work indicate that the choice of FV measurement control parameters does indeed affect FV measurement performance and behaviour. However, one of the most interesting results is that the values of parameters such as S_a are consistent across measurement set-ups. This is comforting as it suggests that FV can be used to measure metal additive surfaces with comparable results across multiple measurement set-ups. If one focuses on the actual topographic detail obtained from reconstruction though, it is not possible to say whether the metrological quality of the reconstructed topographies (in particular in terms of accuracy) is better or worse in some set-ups versus others. This is because neither NMP nor Q3 are suitable indicators for accuracy, and comparison with a more accurate reference is needed. Previous work on the generation of statistical topography models from repeated measurements [4,8] indicates a possible pathway to approach the issue, although measurement results from a higher-accuracy instrument are still needed. In general, the challenge of understanding how uncertainty should be computed and associated to surface topography characterisation is currently unsolved [14].

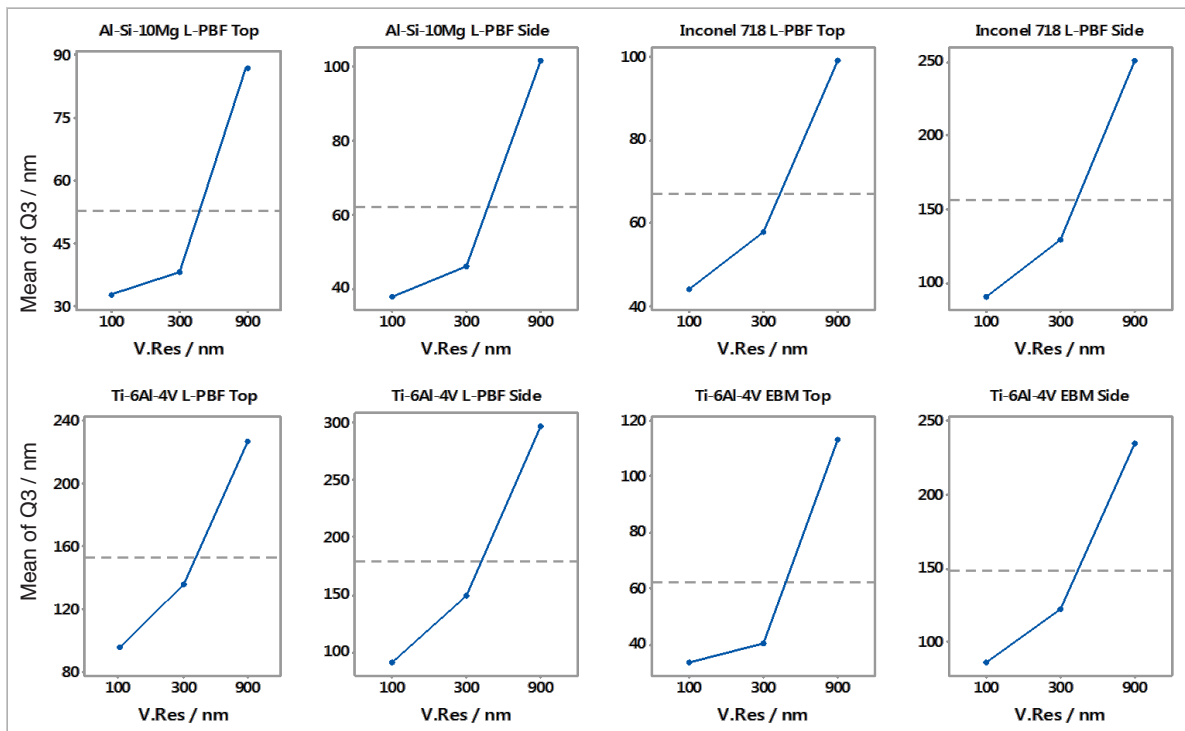


FIGURE 4. Main effect plots of vertical resolution on Q3 at 10 $\times$ magnification ($p < 0.05$ for all the plots).

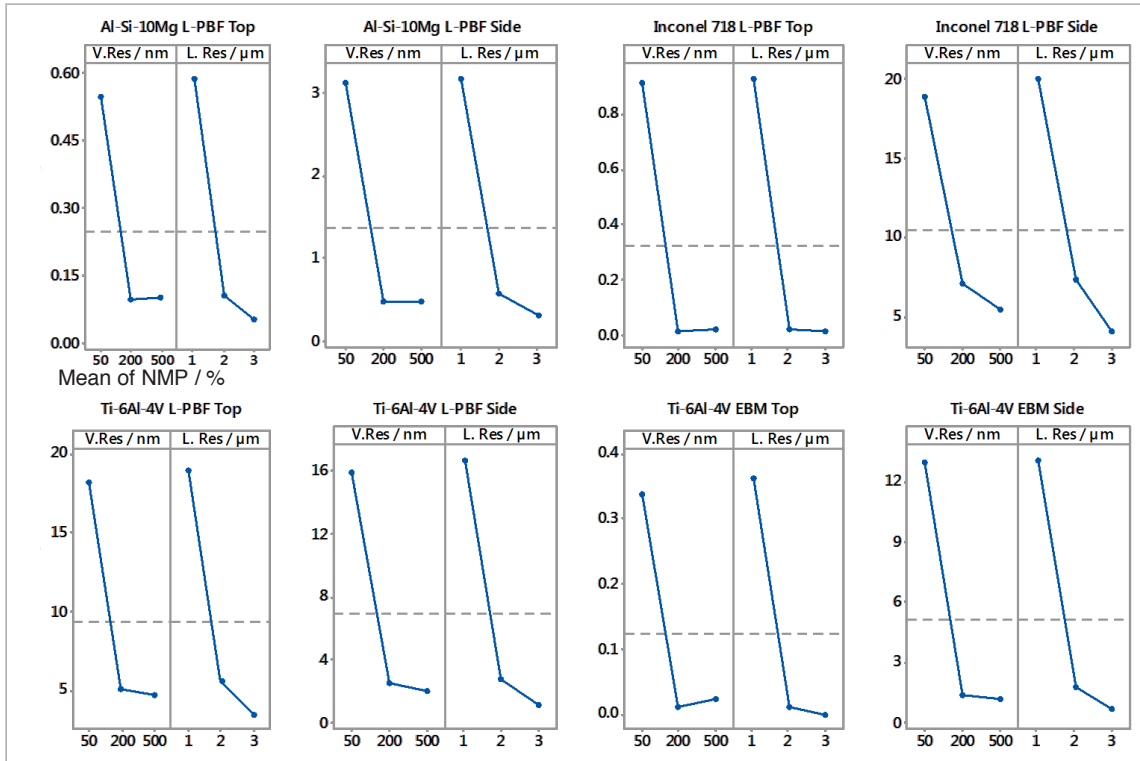


FIGURE 5. Main effect plots of vertical resolution on NMP at 20 $\times$ magnification ($p < 0.05$ for all the plots).

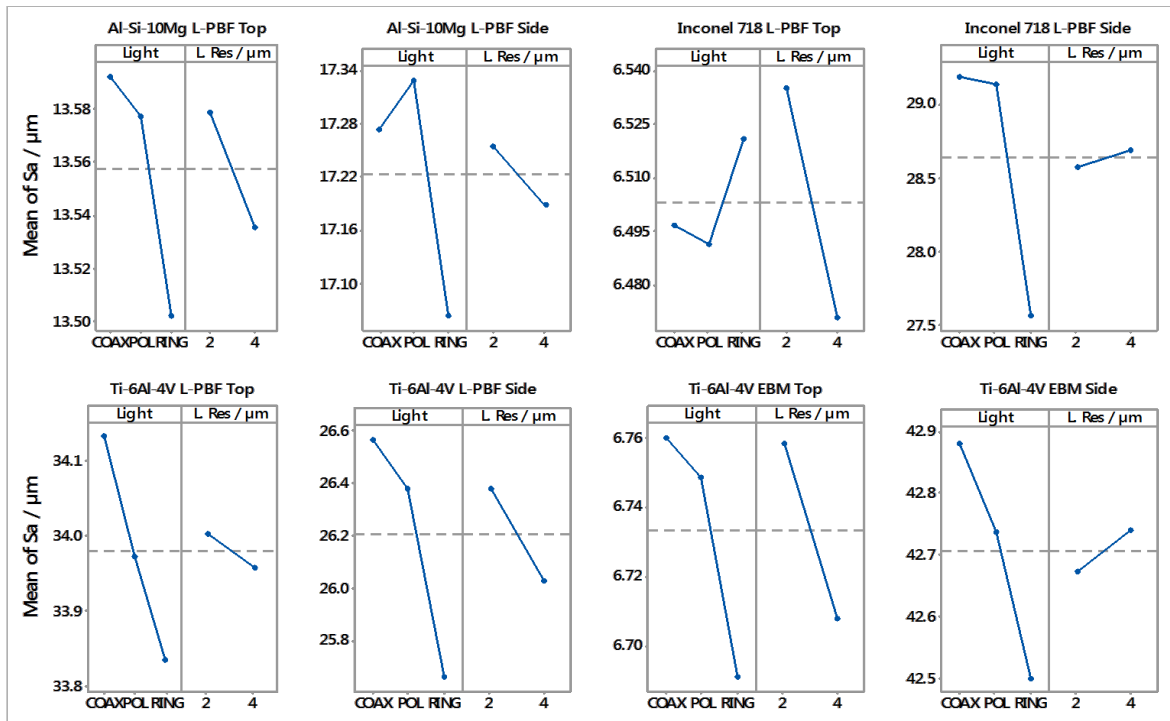


FIGURE 6. Main effect plots of vertical resolution on Sa at 10 $\times$ magnification ($p < 0.05$ for all the plots).

CONCLUSIONS

Metal additive surfaces, produced by PBF processes, present a wide array of topographies, each with their own specific measurement challenges. Despite such variability, some general conclusions have been drawn. The computation of surface texture parameters such as *Sa* (ISO 25178-2 [13]) is mostly unaffected by measurement set-up. However, other indicators such as local repeatability error in height determination and the percentage of non-measured points are significantly affected by the control parameters, although the trends vary with surface type.

FV measurement is a technology with plenty of opportunity for the measurement of complex surfaces, such as those produced by metal AM. Despite the technology being relatively easy to use, there are many parameters that could be changed by an operator leading to different measurement outcomes. Further research, based on the availability of more accurate measurements to act as references, is needed to understand whether such changes represent improvements or not.

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REFERENCES

- [1] Gibson I, Rosen D, Stucker B. Additive Manufacturing Technologies. New York, NY: Springer New York; 2015.
- [2] Townsend A, Senin N, Blunt L, Leach RK, Taylor JS. Surface texture metrology for metal additive manufacturing: a review. *Precis Eng*. 2016;46:34–47.
- [3] Triantaphyllou A, Giusca CL, Macaulay GD, Roerig F, Hoebel M, Leach RK, et al. Surface texture measurement for additive manufacturing. *Surf Topogr Metrol Prop*. 2015;3(2).
- [4] Senin N, Thompson A, Leach RK. Characterisation of the topography of metal additive surface features with different measurement technologies. *Meas Sci Technol*. 2017;28(9).
- [5] Gomez C, Su R, Thompson A, DiSciaccia J, Lawes S, Leach R. Optimisation of surface measurement for metal additive manufacturing using coherence scanning interferometry. *Opt Eng*. 2017;56(11).
- [6] Danzl R, Helml F, Scherer S. Focus variation - A robust technology for high resolution optical 3D surface metrology. *Stroj Vestnik/Journal Mech Eng*. 2011;57(3):245–56.
- [7] Helml F. Focus variations instruments. In: Leach RK, editor. *Optical measurement of surface topography*. Springer Berlin Heidelberg; 2013.
- [8] Thompson A, Senin N, Giusca C, Leach R. Topography of selectively laser melted surfaces: A comparison of different measurement methods. *CIRP Ann*. 2017;66(1):543–6.
- [9] Cabanettes F, Joubert A, Chardon G, Dumas V, Rech J, Grosjean C, et al. Topography of as built surfaces generated in metal additive manufacturing: A multi scale analysis from form to roughness. *Precis Eng*. 2018;52:249–65.
- [10] Wang P, Sin WJ, Nai MLS, Wei J. Effects of processing parameters on surface roughness of additive manufactured Ti-6Al-4V via electron beam melting. *Materials (Basel)*. 2017;10(10):8–14.
- [11] ISO. Geometrical product specification (GPS): Surface texture: Areal, Part 606: Nominal characteristics of non-contact (focus variation) instruments. 2015;
- [12] ISO. ISO 25178-600 (GPS) — Surface texture: Areal — Part 600: Metrological characteristics for areal-topography measuring methods (Draft). 2017;
- [13] ISO. ISO 25178-2 (GPS) - Surface texture: Areal - Part 2: Terms, definitions and surface texture parameters. 2012;
- [14] Haitjema H. Uncertainty in measurement of surface topography. *Surf Topogr Metrol Prop*. 2015;3(3):35004.

HOW LASER SCANNING CONFOCAL MICROSCOPY BENEFITS 3D PRINTING

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INTRODUCTION

Tracing its origins to photo sculpture in the 1860s, three-dimensional (3D) printing has evolved into a powerful and popular technique. Combining computer design and additive manufacturing, it builds up materials point by point and layer by layer, without the need for molds or mechanical machining. Various materials (polymer, metal, ceramic, mineral, etc.) can be used to create complicated shapes that are not easily produced through traditional casting or modeling. 3D printing is used in a wide variety of fields, from research to machining and from medicine to art.

Verifying the quality of 3D-printed components is essential for product quality assurance, process knowledge management, and design improvement. Inspection of the surface of 3D samples can be performed using optical microscopy, digital microscopy, scanning electron microscopy, and so forth. Among the various observation and measurement techniques, laser scanning confocal microscopy (LSCM) is gaining popularity, mainly because it is a noncontact and nondestructive method that requires minimal sample preparation, automates efficiently, and provides single nanometer level resolution. In this paper, we will present these advantages in detail, using the example of the Olympus® LEXT® OLS5000 3D laser confocal scanning microscope.

QUALITY ASSURANCE CHECK AND CONTROL WITH LASER SCANNING CONFOCAL MICROSCOPY

The light source of LSCM is a single wavelength laser beam (405 nm). Pinhole apertures are used to remove out-of-focus haze, offering images with high contrast and resolution. Combining in-plane, point-by-point scans and z-stack scans, LSCM can assemble the x, y, and z axes for each pixel to generate 3D mapping. The lateral resolution of the LEXT OLS5000 microscope is ~200 nm, and the vertical resolution can be as precise as 6 nm, repeatedly. It also has an ultra-high pixel density

(1024 × 1024 by default, up to 4096 × 4096) to get enough information out of the sample surface so that even subtle surface texture can be accurately measured.

Ease of Use

Using a laser as the feedback signal, without any physical contact with samples, LSCM is a true noncontact and nondestructive technique with numerous surface inspection application possibilities, including a wide range of parts, from small chips to large tools and silicon to soft sponges. The flexible design of the LEXT OLS5000 microscope easily accommodates large or irregularly shaped samples. It can hold samples as wide as 300 mm in diameter and as tall as 210 mm, and the long working distance objectives facilitate measurements of concavities as deep as 25 mm (FIGURE 1). In addition, no sample preparation is required, and samples are well preserved from any abrasion or contamination. With the possibility of fully automating the OLS5000 system, clear and precise imaging can be easily acquired with only a few clicks of a mouse.

Fast speed

The microscope's scanning algorithm delivers improved data quality and greater speed to reduce the scan time and streamline your workflow, resulting in better productivity [1]. When measuring the shape of steps on a sample containing near-vertical planes, such as an electronic component or MEMS, the data acquisition time can be reduced by limiting the Z-direction scanning range. A 700 μm step can be measured in about 15 seconds without degrading the accuracy (MPLAPON20x objective) [1].

Versatility

The imaging size is determined by the field of view (FOV) of the objective lenses; for example, 100X objective lenses provide a 128 μm × 128 μm FOV and 5X objectives, a 2570 μm × 2570 μm FOV. It only takes a few seconds to complete an image. With the

motorized stage, users can move the sample with precision, and it is easy to stitch together large, high-resolution images. The LEXT OLS5000 microscope can stitch up to 2500 images into one. Figure 2 shows a 4 × 4 stitched image of a gear with a height of 1.6 mm and a diameter of 2.4 mm, acquired using a 20X objective.

Quantitative measurements of surface features, including line/area roughness, area/volume measurement, particle analysis, edge detection, and film thickness, can be reliably and accurately performed with the LEXT OLS5000 microscope, enabling it to support a large variety of applications.

HOW LASER SCANNING CONFOCAL MICROSCOPY BENEFITS 3D PRINTING

Tolerance Check

The LEXT® OLS5000 microscope can export acquired 3D imaging data of samples in various formats, including STL (mesh data) and CSV (FIGURE 3). Users can open the files via 3D printing design or machining software such as CAD to compare the original design data and STL data of the sample and check for difference, errors and dimensional accuracy during the printing process.

Roughness

Surface metrology provides value in discovering functional correlations between roughness and performance and between processing and roughness. These discoveries depend on good measurement fidelity and resolution as well as analyzing the right geometrical features at the appropriate scales. The method of data analysis is equally important along with the data acquisition capabilities of the measurement instrument. Since three-dimensional surface texture parameters are essential for defining irregular surface features, analysis based on 3D surface texture is important [2].

The broadness of range, fineness, and low-noise characteristics of LEXT deliver measurement results that are essential in the analysis of surface textures. LSCM can provide line roughness and area roughness data of samples. It enables operators to specify the measurement line or area of interest after data acquisition. Surface roughness data indicating the flatness and smoothness of the sample is a very important parameter in quality control (FIGURE 4).

Sidewalls

While measurements of sidewall features (line, trench, or contact holes) and angles can be complex and time-consuming to perform with other microscope techniques, LSCM can quickly and precisely measure irregular shapes and sidewalls at the nanometer level. LSCM has high inclination sensitivity enabling it to make accurate measurements of complex geometric structures with steep sides [3]. Other microscope types typically require additional modules to measure sidewall details; for example, scanning electron microscopes require focused ion beam capabilities (FIB-SEM), and atomic force microscopes (AFM) require tilting stage capabilities. However, the LEXT OLS5000 microscope can resolve sidewalls with angles of up to 87.5° with no additional time or hardware required. Furthermore, sidewall surface roughness data can be acquired at the same time.

Cracks

In the course of the 3D printing process, cracks can occur during the melting and solidification stages. The LEXT OLS5000 can provide the precise shape and dimensions of cracks to help users further improve the design and recipe. Using dual confocal technology, LSCM can acquire a reliable 3D image even for surfaces made up of materials with different reflectivities. It enables users to evaluate the surfaces with heavy irregularities and examine surface features quantitatively [4]. With the microscope's stitching mode, users can combine multiple images to form a single wide-area observation in high resolution, making it easy to identify crack size and depth across a large surface.

CONCLUSION

Owing to its capability to provide accurate 3D measurements on a wide range of sample types and applications, laser scanning confocal microscopy (LSCM) is a powerful and reliable option for obtaining the precision data required for quality assurance and 3D printing process control. With its simple operation, the LEXT OLS5000 microscope provides 3D structure and roughness data and sidewall measurement and roughness quickly and easily. It is a nondestructive, precise, fast, and easy way to perform 3D printing quality assurance inspections.

FIGURES



FIGURE 1a. The LEXT OLS5000 microscope with a ring sample fixed vertically on the stage.



FIGURE 1b. Olympus provides varieties of objective lens including high performance and long working distance ones.

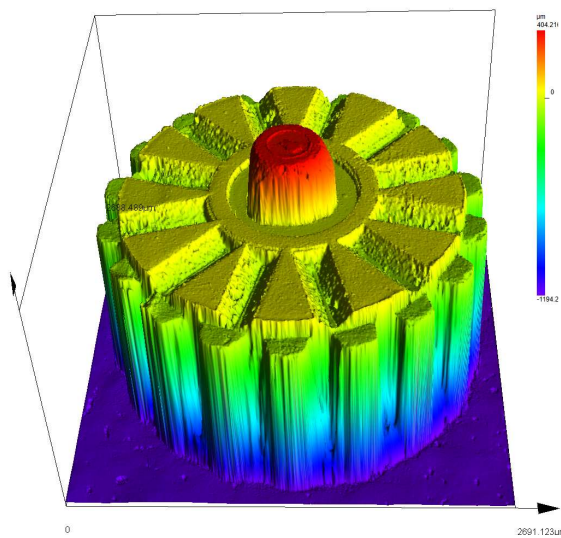


FIGURE 2. A 4×4 stitched image showing a gear measuring 1.6 mm high and 2.4 mm in diameter.

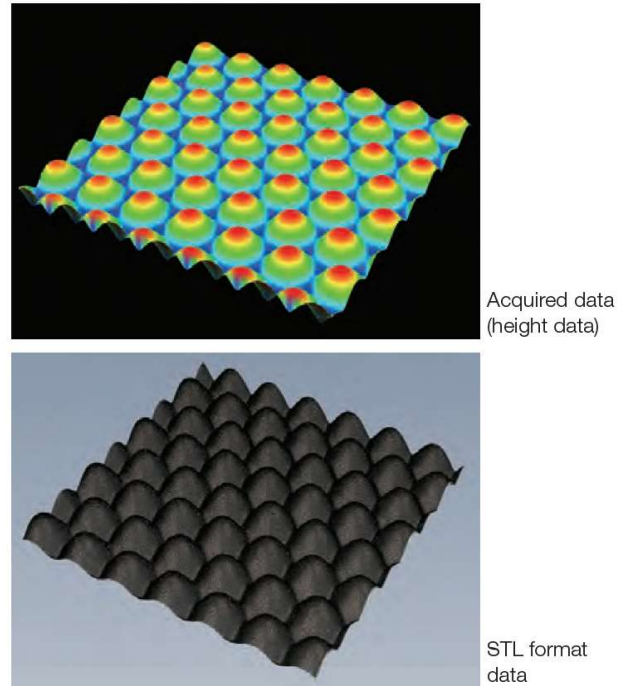


FIGURE 3. Snapshots showing the same data opened with LEXT data analysis software and CAD.

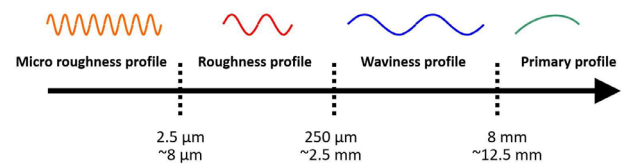
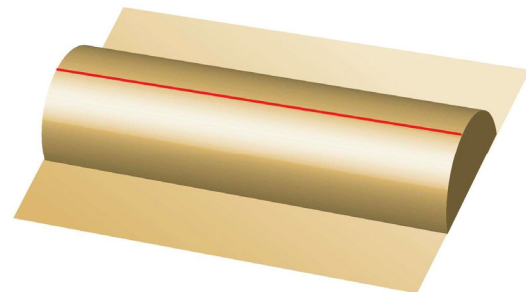


FIGURE 4a. Line roughness measurement of an ultra-thin pipe.

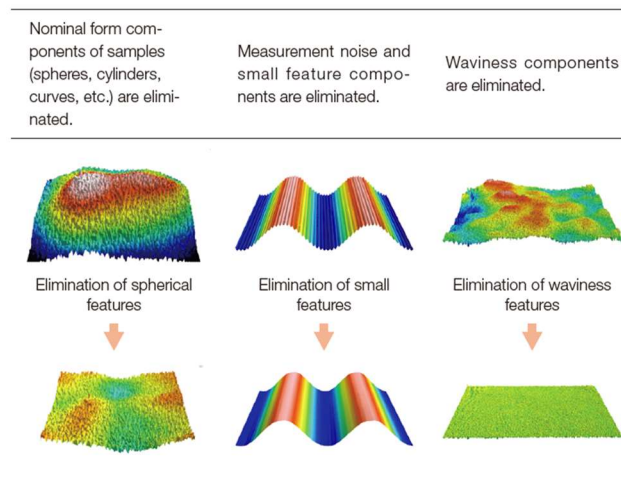


FIGURE 4b. Method of filter application in area roughness measurement.

REFERENCES

- [1] <https://www.olympus-ims.com/en/metrology/ols5000/#cmsContent14024>.
- [2] Olympus Introduction to Surface Roughness Measurement Guidebook
- [3] <https://www.olympus-ims.com/en/applications/ie-surface-observation-of-ink-jet-paper/>.
- [4] <https://www.olympus-ims.com/en/applications/ie-evaluating-the-surface-profile-of-coated-abrasives/>.

MEASUREMENT OF THERMAL PROCESSING VARIABILITY IN POWDER BED FUSION

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INTRODUCTION

Laser powder bed fusion (LPBF) is an additive manufacturing (AM) technology used to manufacture high-value metal parts. The layer-by-layer nature of the process allows complex geometries and internal features, such as conformal cooling channels, to be realized. For the technology to reach its full potential, it must be capable of manufacturing precision parts. However, the precision of parts fabricated using LPBF is currently orders of magnitude worse than what can be achieved using machining [1]. This is due, in part, to the distortion that arises from thermally induced residual stresses [2]. While distortion can be compensated for and/or corrected through post-processing, this is costly and not always possible for internal features.

An additional challenge that LPBF and other metal AM technologies face is that in addition to creating the part geometry, the material is also created during the process. The melting of the metal feedstock powder using a laser and the rapid cooling of the solidified material, as well as the cyclic re-heating and cooling from adjacent tracks and subsequent layers, has a significant impact on microstructure and material properties [3]. Unfortunately, the material of a LPBF manufactured part is inhomogeneous due to the inconsistency of the thermal processing throughout the part. The imprecision arises from a variety of factors, including the scan strategy, processing conditions [4], and geometric effects, such as the reduced ability to conduct heat away from the melt pool when creating overhangs.

Considering the impact on distortion, microstructure, and material performance, the thermal history of the processed material must be understood before precision geometries or materials can be manufactured using LPBF technologies. The objective of this work is to present preliminary results from in situ thermographic measurements acquired during the build of a complex part and to assess the variability of the thermal processing in response to scan strategy and geometry effects.

EXPERIMENT SETUP

FIGURE 1 shows the experiment setup. A commercial powder bed fusion system is modified to allow a high-speed short-wave infrared (SWIR) camera to observe a small region of the build plane. The camera acquires images at a rate of 1800 frames per second and is sensitive to radiant temperatures from 550 °C to 1050 °C. Details on this setup can be found in [5].

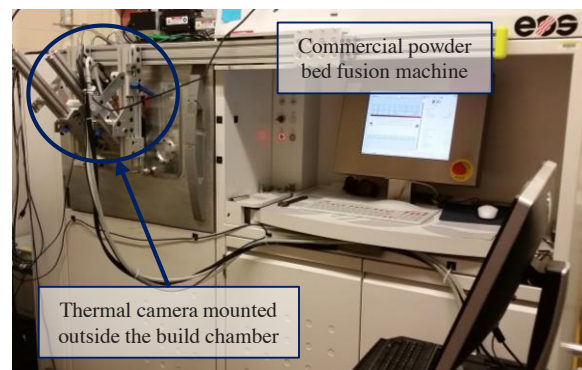


FIGURE 1 - The powder bed fusion system with the infrared camera mounted to it.

² Official contribution of the National Institute of Standards and Technology (NIST); not subject to copyright in the USA. The full descriptions of the procedures used in this paper require the identification of certain commercial products. The inclusion of such information should in no way be construed as indicating that such products are endorsed by NIST or are recommended by NIST or that they are necessarily the best materials, instruments, software, or suppliers for the purposes described.

FIGURE 2 shows the part used in this study, manufactured of nickel-based super alloy 625 (IN 625). FIGURE 3 presents a schematic of the part. The part is designed to be small enough to fit entirely in the field of view of the camera, which is approximately 12 mm x 6 mm. It has a hole on one side and a 45° overhang on the other. The part is manufactured on a 100 mm x 50 mm IN 625 substrate that is 12.7 mm thick. The substrate is bolted on the LPBF build platform.

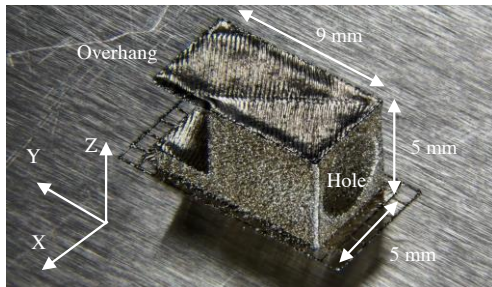


FIGURE 2 - The part used in this study is small enough to fit in the SWIR camera's field of view.

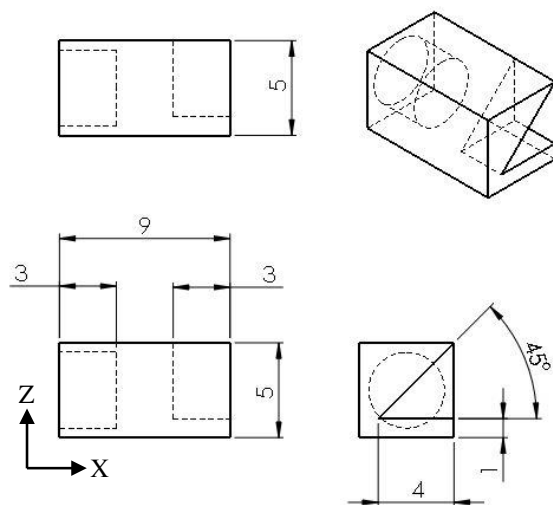


FIGURE 3 – Part schematic. Dimensions in mm.

The part is manufactured in 249 layers. Each layer is 20 μm thick and consists of three steps: a pre-contour scan of the perimeter of the part, a raster scan to fill in the cross section of the part (called “skin” by the manufacturer), and a post-contour scan of the perimeter. This study focuses on the thermal history generated by the raster scan. The raster scan is performed with a programmed laser power of 195 W and a programmed scan speed of 800 mm/s. The hatch spacing (distance between adjacent scan tracks) is 0.1 mm. The raster scans are contained within

“stripes” that are 5 mm wide. These stripes are pre-defined within the build area and rotate 67° between layers. Multiple stripes are used in each layer to scan the entire cross section of the part.

There are four layers of interest due to the part geometry, as shown in FIGURE 4. Layer 25 is the final layer of the 9 mm long 5 mm wide rectangular base. It provides insight into the thermal history unaffected by the hole or overhang features and establishes a baseline to which the other layers can be compared. Layer 125 occurs at the midpoint of the hole where the width of the wall beside it is at a minimum (0.5 mm thick). Layer 226 is performed immediately after the hole is completed and therefore part of the layer is created over powder and not solidified material. Finally, Layer 249 is the final layer, the effects of which are evident in the top of the part (FIGURE 2).

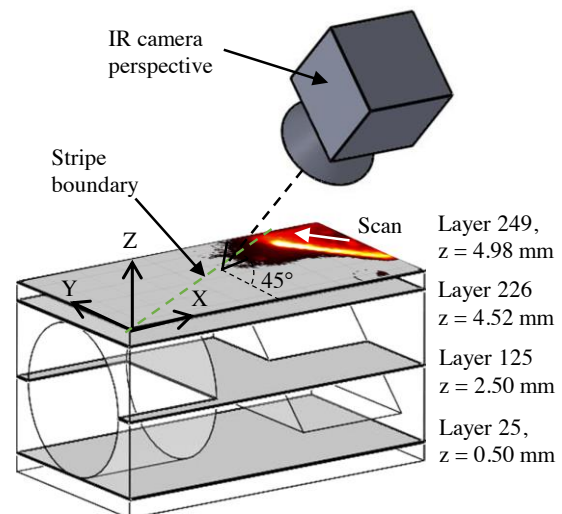


FIGURE 4 - Illustration of the 4 layers of interest and the relative position of the IR camera.

RESULTS AND DISCUSSION

An example thermal video frame acquired during Layer 25 is shown in FIGURE 5. This is one of the 1266 frames acquired during the layer. In this frame (# 617), the laser is scanning through the middle of the part in a 5 mm-wide stripe. The stripe boundary is illustrated with dashed green lines. Ejected material (spatter) is imaged in addition to the melt pool.

FIGURE 6A illustrates the radiant temperature history of a single pixel during the processing of

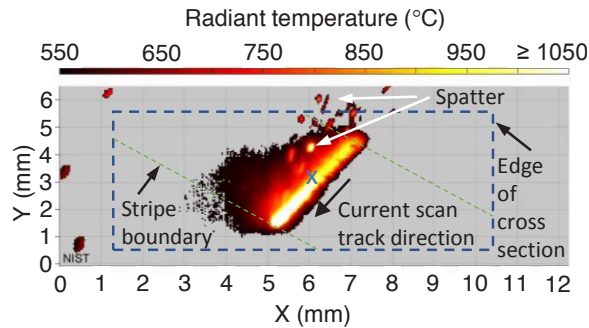


FIGURE 5 - A thermal video frame acquired during Layer 25. The part perimeter is illustrated with the dashed lines. The blue "x" in the center shows the location of the data in FIGURE 6.

Layer 25. This pixel correlates to the location indicated by a blue "x" in FIGURE 5. As expected, the measured radiant temperature fluctuates as the material is re-heated, and (in some cases) re-melted by successive tracks. The oscillation continues as the material cools. Spatter flying between the surface and the camera causes extreme spikes.

FIGURE 6B demonstrates the calculation of the cooling rate for each pixel in a layer. For this study, cooling rate is defined as the rate the material cools from the true temperature of solidification of 1290 °C to 1000 °C. Since the SWIR camera measures radiant temperature and not true temperature, the equivalent radiant temperatures must be determined.

The radiant temperature equivalent to the solidification temperature was identified in prior work [5]. Using the same experiment setup, the solidification plateau was identified and used to measure melt pool length and to identify the solidification radiant temperature when creating laser tracks on bare substrates [5]. A subsequent study demonstrated that the presence of powder does not significantly affect the radiant temperature [7]. Therefore, radiant temperature of solidification determined from bare plate scans (942 °C) is assumed for the multi-layer build.

The radiant and true temperatures of solidification can be used to calculate the effective emissivity using the Sakuma-Hatori equations, which relate the camera signal to a calibrated temperature [8]:

$$F(T) = S = \frac{C}{\exp\left(\frac{C_2}{AT+B}\right)-1} \quad (1)$$

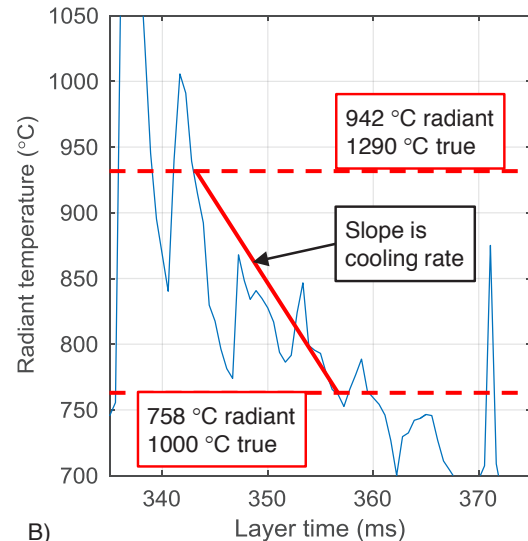
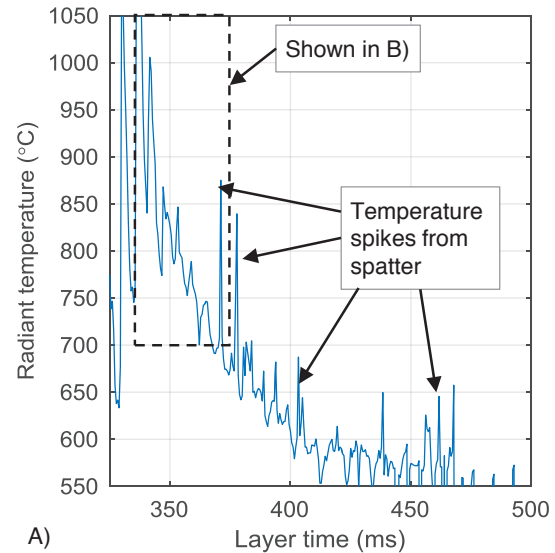


FIGURE 6 - Radiant temperature history at the center of the part in Layer 25.

$$F^{-1}(S) = T_{\text{radiant}} = \frac{c_2}{A \ln\left(\frac{C}{S}+1\right)} - \frac{B}{A} \quad (2)$$

where S is the camera signal, T is temperature in K, c_2 is the second radiation constant (14388 $\mu\text{m}\cdot\text{K}$) and A , B , and C are constants established through a black body calibration. The black body calibration and the resulting constants for this work are presented in [5]. True temperature and radiant temperature are related:

$$F(T_{\text{true}}) \varepsilon = F(T_{\text{radiant}}) \quad (3)$$

where ε is the effective emissivity of the surface. The effective emissivity of the recently solidified material is calculated using Equation 3 and the true and radiant temperatures of the solidification. This calculation yields $\varepsilon = 0.168$. Assuming this

emissivity applies to the material at 1000 °C, the equivalent radiant temperature is 758 °C. Cooling rate is then calculated using:

$$\text{Cooling Rate} = \frac{\Delta T_{\text{true}}}{t_2 - t_1} \quad (4)$$

where ΔT_{true} is the temperature range of interest (in this case, 290 °C), t_1 is the time at that occurrence the pixel drops below the solidification temperature, and t_2 is first time after t_1 that the pixel equals the lower temperature range.

FIGURE 7 presents a map of the cooling rate calculated from the SWIR measurements of Layer 25. This figure shows that cooling rate varies significantly due to both scan strategy and layer shape. The typical behavior within a stripe unaffected by the layer shape is evident in the center region of the layer (outlined with white dashes). The cooling rate is lower in the center of the stripe (approximately 25 000 °C/s) and higher near the edges (more than 50 000 °C/s). This difference is attributed to the material in the middle of the stripe retaining heat longer than at the edges of the strip, decreasing its ability to evacuate the heat input from the laser and thus decreasing the rate at which the material cools. While this trend is expected to be consistent for different stripe widths (a variable that most LPBF users can control), the magnitudes may differ.

Although a typical cooling rate distribution within a stripe can be achieved, the layer shape can significantly alter the scan strategy and ultimately the cooling rates. For instance, the shape of Layer 25 prevents most of the area from being scanned with the programmed stripe width. The stripe width is effectively decreased to scan these narrower areas, and the laser more frequently re-scans near a recently solidified region, thus

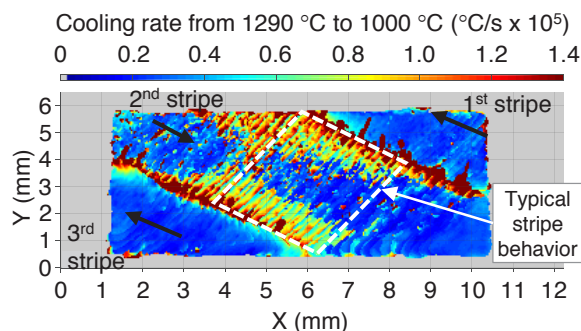


FIGURE 7 – Map of the cooling rate in Layer 25.

keeping the material hotter and reducing the material's ability to evacuate heat input from the laser. Additionally, the timing of the laser seems to be affected when the geometry decreases the stripe width [6], slightly increasing the time between the end of one scan track and the beginning of the next. These two factors explain the lower cooling rates in the 1st and 3rd stripes that fill the upper right and lower left corners of the layer, and the beginning and end of the 2nd stripe across the center of the layer.

Histograms are used to assess the cooling rate as a percentage of area within a layer or region of interest. FIGURE 8 compares the typical stripe (region in FIGURE 7), Layer 25, and all layers from 1 through 25 (considered a baseline for analysis of the rest of the layers). Three observations are made from these histograms. First, within a typical stripe (in this build), two distinct cooling rates occur, where the edges of the stripe cool more approximately 3 times faster than the center of the stripe. Second, the effective decreasing of the stripe width to complete a layer increases the occurrence of lower cooling rate (comparing Layer 25 to the typical stripe). Third, Layer 25 is representative of the baseline established using all preceding layers, (similarity between the two histograms).

FIGURE 9 shows the cooling rate calculations and analysis of Layer 125, which demonstrates the impact of the narrow features on either side of the hole. The analysis reveals that the cooling rate in the narrow features increases by a factor of 2 to approximately 50 000 °C/s, whereas the cooling rate in the rest of the layer remains comparable to the baseline. These results are

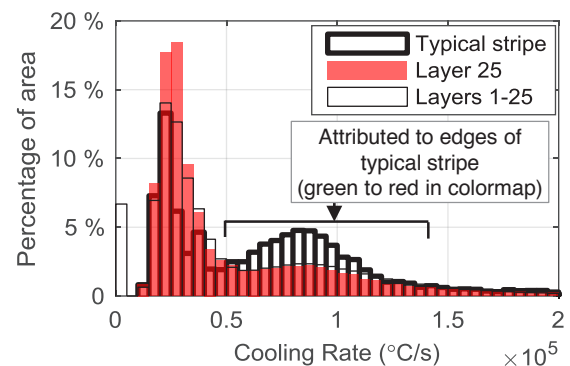


FIGURE 8 - Histogram showing cooling rate as a function of area within the layer.

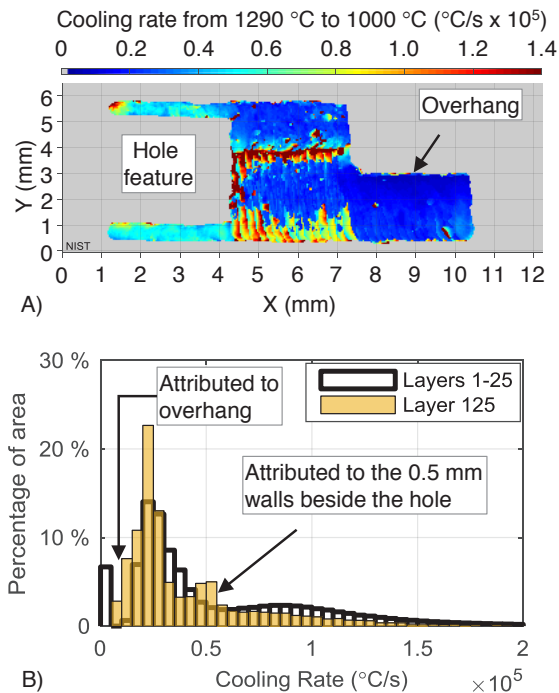


FIGURE 9 - Cooling rate measured during Layer 125. A) Measured cooling rate at each pixel in the layer, B) comparison with Layers 1 through 25.

counter-intuitive for two reasons. First, the narrow scans are performed on material that is surrounded by a greater percentage of powder, which is insulative, compared to the bulk. The higher thermal resistance would theoretically lead to slower cooling rates. Second, the stripe width in these features is much narrower than typical. It has been demonstrated earlier that this decreases cooling rate. However, the increased cooling rate in these narrow features may result from the ratio between laser-on and laser-off times decreasing. The laser shutter is open for a very short duration to scan the 0.5 mm wide features, while the time between successive laser tracks is not significantly impacted. Furthermore, the time to scan each of the narrow features is very quick, potentially impacting of material pre-heating which can decrease conductivity. Further experimental and modeling efforts are required confirm these hypotheses.

FIGURE 10 presents the cooling rate in Layer 226 and compares the results to the baseline. This layer occurs immediately after the completion of the hole feature. FIGURE 10A shows that while a portion of the stripe above the

hole experiences cooling rates slower than expected in a typical stripe, a small portion directly above the top of the hole experiences a higher cooling rate. The lower cooling rate is caused by the geometry, since there is less solid mass below the layer to conduct heat away, while the small region with a higher cooling rate is a result of the scan strategy, as explained below.

The thermal video of Layer 226 shows that most of the stripe is executed as expected, but the laser skips over a small area directly above the hole. After all the stripes are completed, the laser then scans the area that was skipped over. This scan after the completion of all the stripes is referred to by the manufacturer as a “down-skin” and is used for material with powder directly underneath the layer. The “down-skin” is performed with process parameters that produce a shallower melt pool, minimizing the chance of over-melting. Although these “down-skin” scans are performed with little or no solid material underneath, the cooling rate is faster for two reasons. First, the altered processing parameters used for these scans results in lower energy and less heating of the part. Second, the surrounding material to the sides of this regions is better able

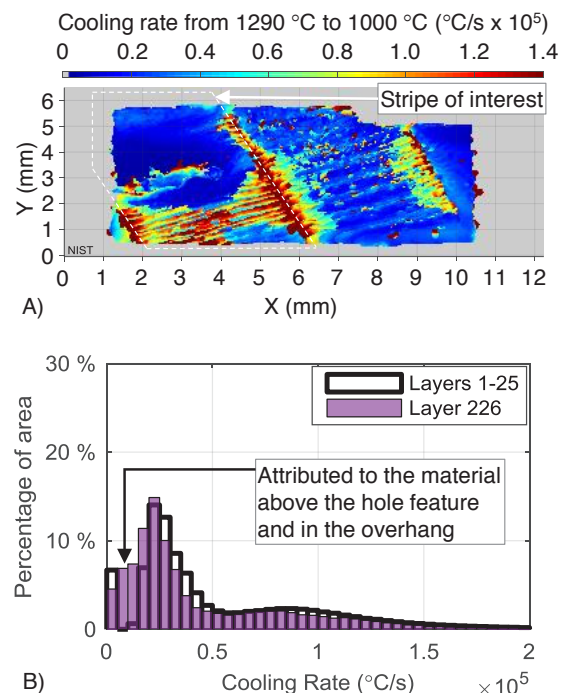


FIGURE 10 - Cooling rate measured during Layer 226. A) Measured cooling rate at each pixel in the layer, B) comparison with Layers 1 through 25.

to conduct heat away because it has had a chance to cool down from the prior stripe scans.

FIGURE 11 presents the cooling rates from the final layer, Layer 249. In general, the cooling rates are similar to the Layer 25, though the material at the overhang experiences a slightly slower cooling rate. However, the reduction in cooling rate at the overhang is not as drastic as above the hole (in Layer 226, FIGURE 10), likely because the overhang is 45°, whereas above the hole a much more extreme overhang is created.

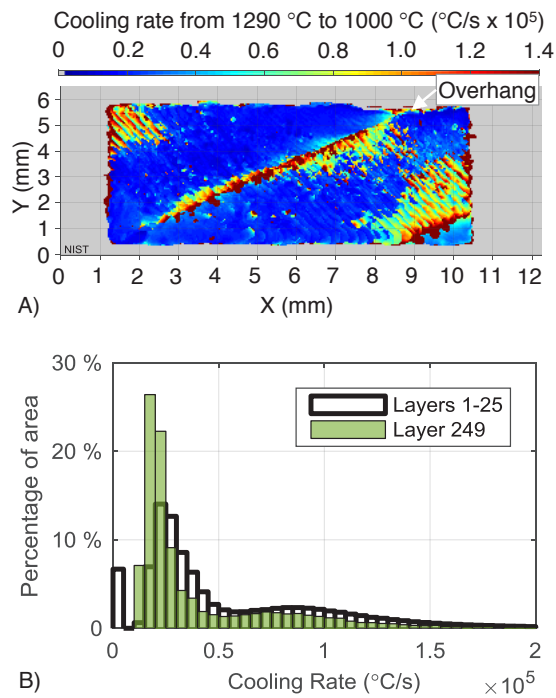


FIGURE 11 - Cooling rate measured during Layer 249. A) Measured cooling rate at each pixel in the layer, B) comparison with Layers 1 through 25.

SUMMARY AND FUTURE WORK

The in situ measurements in this study reveal that the thermal processing in LPBF is extremely imprecise. Both geometry and scan strategy are shown to increase and/or decrease the cooling rates by several factors, and the interaction between the two is complex. Although improvements can be made to improve the thermal processing precision, research must first be conducted to determine the level of precision required to achieve consistent microstructure, material properties, and stresses in the part.

REFERENCES

- [1] F.-W. Goudsmit, G. Oosterhuis, E. Sluiter, and T. Peijnenburg, (2014) Typical requirements for precision mechanical parts and opportunities for additive manufacturing, *Proceedings of the ASPE Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing*, Berkeley, CA, pp. 51–55.
- [2] P. Mercelis and J.-P. Kruth, (2006) Residual stresses in selective laser sintering and selective laser melting, *Rapid Prototyping Journal*, 12(5), pp. 54–265.
- [3] T. Keller, G. Lindwall, S. Ghosh, L. Ma, B.M. Lane, F. Zhang, U.R. Kattner, E.A. Lass, J.C. Heigel, Y. Idell, M.E. Williams, A.J. Allen, J.E. Guyer, L.E. Levine, (2018) Application of finite element, phase-field, and CALPHAD-based methods to additive manufacturing of Ni-based superalloys, *Acta Materialia*, 139, pp. 244-253.
- [4] Y.M. Arisoy, L.E. Ciales, T. Özel, B. Lane, S. Moylan, & A. Donmez, (2017). Influence of scan strategy and process parameters on microstructure and its optimization in additively manufactured nickel alloy 625 via laser powder bed fusion. *The International Journal of Advanced Manufacturing Technology*, 90(5-8), pp. 1393-1417.
- [5] J.C. Heigel and B.M. Lane, (2018) Measurement of the melt pool length during single scan tracks in a commercial laser powder bed fusion process, *Journal of Manufacturing Science and Engineering*, 140(5).
- [6] Additive Manufacturing Benchmark Test Series (AM-Bench): Class 1 benchmark test description. <https://www.nist.gov/ambench/amb2018-01-description>
- [7] J.C. Heigel, and B.M. Lane, (2017) The effect of powder on cooling rate and melt pool length measurements using in situ thermographic techniques, *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference*, pp. 1340-1348.
- [8] B. Lane and E.P. Whiteman, (2015) Calibration and Measurement Procedures for a High Magnification Thermal Camera, *NIST Interagency/Internal Report (NISTIR) – 8098*.

DESIGN OF A MULTI-SENSOR IN-SITU INSPECTION SYSTEM FOR ADDITIVE MANUFACTURING

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INTRODUCTION

Additive manufacturing (AM) of metal parts by laser powder bed fusion (L-PBF) offers high value industries a route to produce components with high complexity, short supply chains and short product development times. These advantages are tempered by uncertainty over the integrity, accuracy and quality of components fabricated by L-PBF, when compared to more established subtractive manufacturing methods. If the process control and geometric qualification of L-PBF parts can be improved through in-process metrology, confidence will increase and industrial uptake will likely improve significantly [1].

In recent years, in-situ methods of process monitoring and simple metrological techniques have been implemented for L-PBF systems by researchers, summarised in two major reviews [2, 3]. In-process inspection of geometric discrepancies could allow for corrective action to be carried out, reducing system waste as well as giving the potential for rapid single build parameter optimisation without the need to remove the component from the chamber. The harsh environment of the L-PBF process, created by the need for a low pressure inert atmosphere and the ejection of molten materials from the laser melting of powdered material, make the placement and protection of any inspection system challenging. One system that has been integrated into a commercial AM machine is Renishaw's InfiniAM Spectral AM process monitoring technology [4]. Their system integrates photodiodes into the machine's laser optics to allow for real-time measurement of the delivered laser energy, the intensity of the resulting plasma and the thermal emissions of the melt pool. The acquisition rate of these photodiodes is 100 kHz, allowing for measurements to be made quick enough to keep pace with the scanning scan of the process laser. Renishaw have been able to create three-dimensional models of the laser energy that has been delivered to each part of the

components, as well as the melt pool's thermal and visible response, that can be used to identify when and where a defect may have occurred. The live identification of signal anomalies that indicate the occurrence of a defect allows for in-layer defect correction to be performed before the build is continued.

Thermographic observation of the melt pool, and of the temperature distribution and heat flow within the wider powder bed [5, 6], have been shown to predict defects such as porosity [7]. However, there remain unresolved challenges in determining an appropriate value of emissivity for correcting the IR images collected [8].

In addition to thermal observations, optical systems have been proposed to capture real-time geometric data during the AM process for individual layers by means of a phase shifting fringe projection technique. Fringe projection methods have been demonstrated as being capable of imaging AM layers in high resolution, but are limited by a small field of view compared to the size of the build plate [9]. A larger field of view has been achieved on a system that uses two cameras to perform fringe projection with a trade off in the level of detail due to image distortion errors [10]. Low coherence interferometry has also been shown capable of performing in-process measurements through the integration of a Michelson interferometer into the process laser's optical system [11]. After the AM layer has been melted, the process laser is turned off and the optical system is used to scan the build area with the laser positioning system of the machine, building a height map of the surface. Although this allows for the scanned area to be focussed on only the regions of interest, meaning that it can be optimised for the size of the part being built, the low scan speed (~20 s scanning time for a 4.4 cm × 4.4 cm height map) means that it is not ideal for a layer by layer measurement in a commercial system for defect detection without a significant increase in the acquisition speed.

High resolution optical imaging combined with multiple individual flash configurations have been used to perform layer by layer measurements of the build process capable of detecting defects through the application of supervised machine learning. For each layer, eight images are taken using different angles of illumination [12]. This work concluded that for a higher level of accuracy when using optical imaging it is essential to collect multiple different images under multiple lighting conditions.

The process monitoring technologies currently being developed are a step in the right direction for the manufacturing technology, however, technical improvements, such as resolution improvements and a larger field of view across the powder bed, and design improvements that allow for further commercial integration must be made to allow for industry to truly benefit from the unique advantages of AM technologies.

A difficulty for in-process measurement of L-PBF comes from the complex features and geometries that occur as a result of the method. Features such as spatter, weld ripples and high porosity create a challenging surface to be measured by most metrology systems [2, 13]. The complex nature of AM surfaces, with high roughness, steep slopes and textures over a wide range of scales, can lead to errors and imaging artefacts when employing a single optical measurement technique [14]. To address these issues, the system presented in this paper employs multiple measurement techniques with the aim of fusing the data to produce a more accurate and/or useful estimate of the topography of an AM layer.

METHODOLOGY

We are developing a system for in-process inspection of an L-PBF machine with a powder bed that is 250 mm × 250 mm in size. The technique under development is shown as a conceptual illustration in *FIGURE 1*. The system will use fringe projection, photogrammetry [Stravroulakis] and thermography with the aim of performing in-process monitoring of the AM build. Additionally, a technique that uses a distributed array of LED light sources, will be used to estimate the local degree of light scatter occurring at the surface. The data collected from these techniques will be intelligently fused for the best possible determination of the surface.

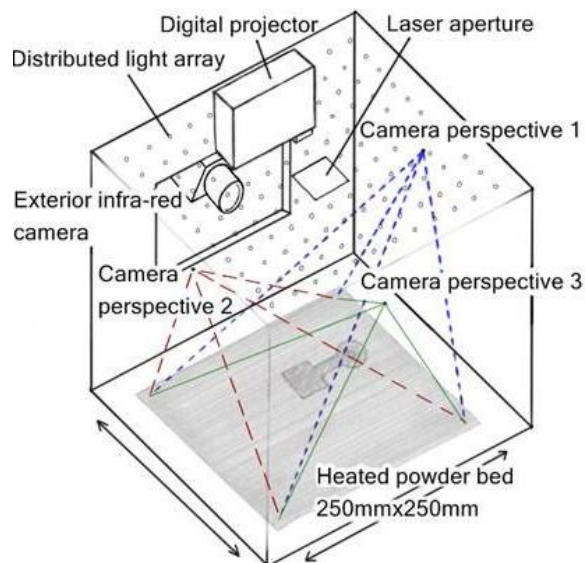


FIGURE 1. Illustration of the proposed system.

The complete system will be used to image individual layers of the build process after the laser has completed its pass across the surface. Although in an ideal situation this would be performed on every layer of the build, this is not realistic with the current hardware due to a maximum acquisition of three frames per second for the cameras. The additional time that the building process would need to be paused for the system to complete a measurement on each layer would likely increase build time for a part beyond what would be deemed worthwhile to most industries. Because of these constraints, the first stage of in-process validation of this system will not be used to measure each layer in the build process. In practice, an intermittent inspection system is likely to provide a lower confidence of defect detection than a continuous inspection system. Although this time constraint is a limiting factor with the current prototype of the system, it could potentially be removed in future iterations with the use of high specification cameras rather than commercially available DSLRs, assuming that the image processing time is comparable to the acquisition rate. The data acquired from the current layer can then be used to make a decision about whether or not the build can continue on its original course, continue with corrective action, or be terminated depending on the severity of the defect identified.

The proposed technique is being developed to achieve a spatial resolution that allows for identification of a number of process fingerprints: weld tracks (nominally 100 μm in width),

elongated pores (50 μm to 500 μm in width and length), balling and unfused powder (100 μm to 150 μm in diameter) [2].

System hardware comprises a 4K projector, an RGB LED array, and two 18 MP DSLR cameras. Later, a thermographic camera will be added. The cameras, positioned to provide a flat and focused image of the build area from multiple perspectives, will be used in each of the three visible light methods. The layout must also meet the demands of the limited volume of a L-PBF system; the prototype will be installed within a decommissioned commercial L-PBF machine. To assist with these limitations the L-PBF build chamber was modelled in CAD software, as can be seen in *FIGURE 2*. Due to the space restraints of the system, cameras cannot be installed with their line-of-sight perpendicular to the surface being imaged. The inclusion of an angular component between the camera's imaging path and the build plate means that it is not possible to have the whole surface in focus using a standard lens configuration. To resolve this issue, each of the cameras have been fitted with a tilt shift lens system that allows for the angle of the focal path to be adjusted relative to the camera and, therefore, made parallel to the surface being imaged.

The location of the projector component of the fringe projection system is particularly challenging. This proposed system design has achieved a lateral projected pixel size of $<120\ \mu\text{m}$ and the DSLR cameras have an equivalent pixel imaging size of $<40\ \mu\text{m}$ on the powder bed. The IR camera to be used alongside the optical system must be capable of measuring temperatures experienced across the powder bed after the laser has completed the pass on each layer. Ti-6Al-4V bed temperatures post laser pass have been observed to be up to 800 °C [6], meaning that the IR camera selected must be capable of observing these temperatures at a minimum. To observe how the temperature flows throughout the layer post lasing, the camera must also be capable of capturing more than a single image each layer. With a capture time of 40 ms per image, a 25 Hz IR camera would meet the frame rate requirements to provide a strong indication of where heat build-up occurs on the most recently printed layer.

A prototype of the multi-sensor system is currently being developed on a dedicated frame (shown in *FIGURE 3*), prior to integration into a commercial L-PBF chassis, thereby relaxing the

spatial constraints. Fringe projection and photogrammetry both use the DSLRs and the projector for the acquisition of data. The photogrammetry system will utilise the projector to provide additional texture to the powder bed surface to assist in identifying correspondences between the two images [15]. When applying fringe projection, photogrammetry or thermographic measurement techniques, assumptions are being made about the degree of light scatter that is occurring at the surface. For multi-camera systems, the surface normal is also a consideration. As noted earlier, the function of the LED array is to provide a better means for combining the topography data from the complementary techniques by determining a measure of the surface normal angle and the degree of scattering that is occurring at every point of the surface that is being observed as a pixel in the camera images. To achieve this, the LED array can be illuminated in a series of patterns, for example a moving column or row of LEDs. As the illuminated pattern is moved across the array the angle from the illumination to the camera apertures will change. From knowledge of the position of the illuminated LEDs, powder bed and cameras, within a registered coordinate system, a measure can be made of the surface's normal angle and degree of scattering by observing the intensity of each pixel in the camera images. The LED data will be relatively coarse compared to the high resolution form and texture measurement, but is expected to provide a useful differential when assigning weightings to fusion of topographic data. The exact illumination strategy is yet to be determined.

The development of this instrument is at an early stage. The hardware is being assembled on a test bench frame. The system will then be calibrated against traceable reference artefacts and the resolution capabilities of the system will be assessed against pre-manufactured workpiece-like L-PBF artefacts validated against a suite of other traceable measurement systems. Following the acquisition and validation of data, the authors will develop the point cloud data fusion techniques.

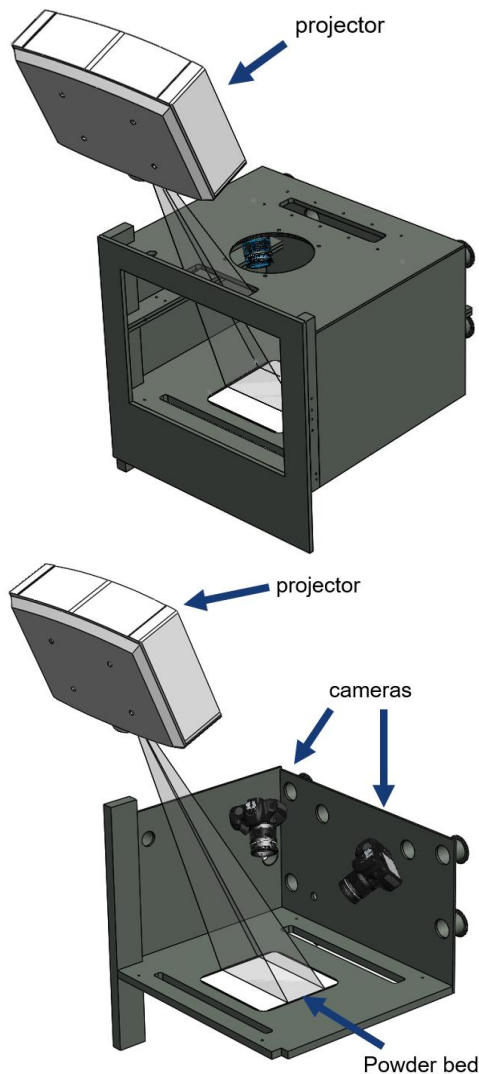


FIGURE 2. CAD models of AM250 build chamber used to determine space limitations in the design of the system. (Top) Closed model, demonstrating how the projector projects into the build chamber. (Bottom) Internal view demonstrating the position if cameras within the chamber.

CONCLUSION

The aim of this prototype is not to create a system that will be used to acquire high resolution data for each individual layer of the build process, as this would result in component build times exceeding what industry would deem acceptable. Instead, the system is intended to acquire layer-by-layer low resolution thermal data that can be used to determine when a higher resolution image is necessary to detect build errors. A side product of the system would also

allow for the set-up and optimisation of new L-PBF systems or for rapid single component parameter optimisation of critical components or new materials, eliminating the need to produce whole parts when optimising parameters. By doing this optimisation, the user can have a higher level of confidence in the quality of their component without such a heavy reliance on external post-process measurements after the component is complete.

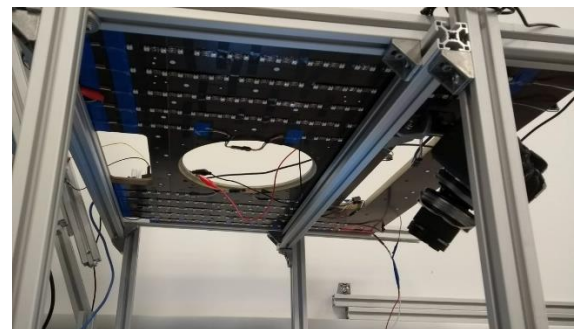


FIGURE 3. (Top) Current out-of-machine set up of the system, built around the dimensions of the CAD model show in FIGURE 2. (Bottom) LED array placed on the underside of an AM 250's chamber top panel replica.

With the current progress being made in L-PBF machinery, an in-process system such as the one being developed could accelerate the adoption of powder-based processes in industry if implemented into future generations of machines. By reducing both time and material waste in manufacturing and allowing for a faster method of parameter optimisation, it has the potential to make AM more economically viable and provide a greater level of confidence in the dimensional accuracies of the components being manufactured.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] Slaughter A, Yampolskiy M, Matthews M, King W, Guss G, Elovici Y. How to Ensure Bad Quality in Metal Additive Manufacturing. Proceedings of the 12th International Conference on Availability, Reliability and Security. 2017: 1–10.
- [2] Everton S, Hirsch M, Stravroulakis P, Leach R K, Clare A. Review of In-situ Process Monitoring and In-situ Metrology for Metal Additive Manufacturing. Materials & Design. 2016; 95: 431–445.
- [3] Grasso M, Colosimo B. Process Defects In Situ Monitoring Methods in Metal Powder Bed Fusion: A Review. Measurement Science and Technology. 2017; 28: 044005.
- [4] Saunders M. Real-time AM Monitoring Opens Up New Process Control Opportunities. Available: <https://linkedin.com/pulse/real-time-am-monitoring-opens-up-new-process-control-marc-saunders/>. 2018. Last accessed: 18/06/18
- [5] Krauss H, Eschey C, Zaeh M. Thermography for Monitoring the Selective Laser Melting Process. Proceedings of the Solid Freeform Fabrication Symposium. 2012: 999–1014.
- [6] Rodriguez E, Medina F, Espalin D, Terrazas C, Muse D, Henry C, MacDonald E, Wicker R. Integration of a Thermal Imaging Feedback Control System in Electron Beam Melting. Proceedings of the Solid Freeform Fabrication. 2012: 945–961.
- [7] Khanzadeh M, Chowdhury S, Tschopp M. A, Doude H, Marufuzzaman M, Bian L. In-Situ Monitoring of Melt Pool Images for Porosity Prediction in Directed Energy Deposition Processes. IISE Transactions. 2017: 1-19.
- [8] Lane B, Moylan S, Whitenton E, Ma L. Thermographic Measurements of the Commercial Laser Powder Bed Fusion Process at NIST. Rapid Prototyping Journal. 2016; 22: 778-787.
- [9] Zhang B, Ziegert J, Faramarz F, Davies A. In situ Surface topography of Laser Powder Bed Fusion Using Fringe Projection. Additive Manufacturing. 2016; 12: 100-107.
- [10] Land W, Zhang B, Ziegert J, Davies A. In-Situ Metrology System for Laser Powder Bed Fusion Additive Process. Procedia Manufacturing 2015; 1: 393–403.
- [11] DePond P, Guss G, Ly S, Calta N, Deane D, Khairallah S, Matthews M. In situ Measurements of Layer Roughness during Laser Powder Bed Fusion Additive Manufacturing Using Low coherence Scanning Interferometry. Materials and Design. 2018; 154: 347-359.
- [12] Gobert C, Reutzel E, Petrich J, Nassar A, Phoha S. Application of Supervised Machine Learning for Defect Detecton During Metallic Powder Bed Fusion Additive Manufacturing Using High Resolution Imaging. Additive Manufacturing. 2018; 21: 517-528.
- [13] Stravroulakis P, Leach R K. Review of Post-Process Optical Form Metrology for Industrial-Grade Metal Additive Manufactured Parts. Review of Scientific Instruments. 2016; 87: 041101.
- [14] Thompson A, Senin N, Giusca C, Leach R. Topography of Selectively Laser Melted Surfaces: A Comparison of Different Measurement Methods. CIRP Annals – Manufacturing Technology. 2017; 66: 543-546.
- [15] Sims-Waterhouse D, Piano S, Leach R K. Verification of Micro-Scale Photogrammetry for Smooth Three-Dimensional Object Measurement. Measurement Science and Technology. 2017; 28: 055010.

LAYERWISE IMAGING FOR IN-SITU METROLOGY IN LASER POWDER BED FUSION PROCESS: A PRELIMINARY STUDY

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1. INTRODUCTION

Laser Powder Bed Fusion (LPBF) is becoming more and more attractive in industry for the production of functional parts, especially in sectors where customization, innovative materials and complex geometries represent the major added value. Nevertheless, stability and repeatability of LPBF processes represents one of the major barrier to their industrial take off because of the stringent quality requirements. For these reasons, current research trends aim to identify innovative solutions for in-situ monitoring and inspection to quickly detect the onset of defects during the process in a zero-defect oriented framework.

In particular, the layerwise nature of the process allows one to capture the picture of each printed layer. As pointed out in literature [1], layerwise imaging in LPBF could be used to identify geometric features to measure the dimensional accuracy of each layer, reconstruct the 3D geometry of the part on a layer-by-layer basis providing then a volumetric representation of the part) and detect powder contamination flaws and other powder recoating errors. All these tasks rely on the capability of segmenting a image into a foreground region, corresponding to the printed slice, and a background region, corresponding to the loose powder in the powder bed. Nowadays, almost all LPBF systems are equipped with off-axial cameras capturing pictures of each layer. However, there is still a lack of studies aimed at fostering the use of image-based reconstruction as an on-line metrological tool to acquire the printed geometry at each layer.

The present study aims to fill this gap by analyzing the accuracy and precision of in-situ dimensional measurements based on layerwise slice contour identification. This represent a first necessary step to the development of in-situ part quality inspection. In particular, this study addresses several points affecting the performance of in-situ dimensional and geometric inspection via image analysis, namely:

1. The effect of different illumination conditions;
2. The effect of the scan direction;
3. The build-to-build variability;
4. The location effect within the build area;
5. The in-situ dimensional accuracy and precision for different geometric features.

This short paper is organized as follows:

Section 2 briefly reviews the state of the art. Section 3 presents the proposed methodology. Section 4 describes the experimental setup; Section 5 presents the major results; finally, Section 6 concludes the extended abstract.

2. STATE OF THE ART

In recent years, various authors studied the use of layerwise imaging to characterize either the homogeneity of the powder bed or the properties of the printed area in terms of surface pattern, geometry, and local thickness profile. Kleszczynski et al. [2] showed that high resolution layerwise imaging coupled with suitable lighting conditions allows one to detect recoating errors together with super-elevations within the printed area. Following studies proposed methods to detect super-elevated edges via layerwise imaging [3] and combining in-situ imaging with recoating blade vibration measurements [4]. Foster et al. [5] proposed a 3D reconstruction method of the part geometry to determine the dimensional accuracy and to detect powder contamination and recoating errors. The idea to use layerwise imaging for in-situ metrology was further developed by Land et al. [6], who proposed a monitoring system that combined off-axis cameras and a fringe projector to measure the topography map of both the scanned slice and the un-melted powder surface in each layer. However, none of the aforementioned studies faced the problem of segmenting the image to separate the printed area from the powder bed nor the accuracy and the precision of the resulting approach.

In order to answer the first issue, Abdelraham et al. [7] proposed a method to detect surface anomalies related to uneven surface patterns within the laser printed area. An active contour algorithm was proposed to detect the contour of the slice in a calibration phase to register the nominal slice to in-situ images. To this aim, the active contours methodology was proposed also by Li et al. [8], for layerwise imaging segmentation in the framework of a 3D geometrical reconstruction of the part. In this case, the active contours algorithm was used to identify the region of interest consisting of the printed area within the layer, and then a topography map was estimated via fringe projection coupled to stereo imaging.

3. METHODOLOGY

3.1 Choice of segmentation algorithm

In this study, the active contours methodology [7-9] was used to segment the layerwise images into a foreground region (the printed slice) and the background (loose powder). Abdelraham et al. and Li et al. [7-8], showed that the active contours methodology is suitable to deal with the particular nature of in-situ layerwise images of the powder bed (noisy background pattern caused by light reflections of loose powder particles, not well defined edges, non-homogeneous foreground pixel intensity patterns caused by uneven surfaces, etc.).

Two algorithms are characterized and compared: the active contours without edges (ACWE) method proposed by Chan and Vese [9] and implemented by Li et al., [7], and the Level set Estimation-Bias Field Estimation (LSE BFE) method proposed by Li et al. [8] and implemented by Abdelraham et al [7].

3.1 Performance characterization

In order to determine the accuracy of the in-situ image segmentation and resulting dimensional measurements, the following the approach was used:

1. Different specimens within the same building area were produced via LPBF with default process parameters;
2. The process was interrupted after a pre-defined number of layers (no top-skin scanning was performed while producing the last layer);
3. In-situ high-resolution images were acquired before and after the laser scan in the last layer under different lighting conditions;

4. A reference measurement of the part was carried out on an optical coordinate measuring system equipped with a reference software

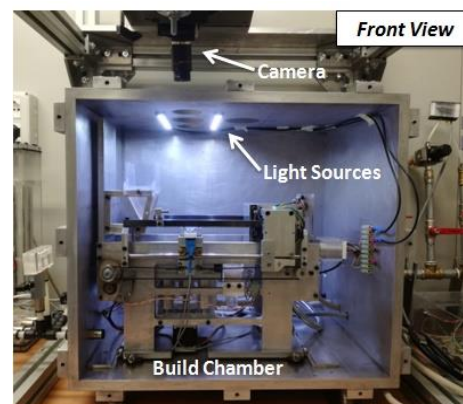
The comparison between the in-situ segmentation and the reference measurement result (also called measurement standard or ground truth) was performed in two ways. First, a supervised similarity criterion was used to calibrate the active contours methods and to screen out lighting conditions that yielded low quality results. The Dice's similarity index was then used for segmentation quality assessment [10].

Once the algorithms had been calibrated and only lighting conditions providing highest quality segmentations (i.e., highest Dice's index values) were retained, a more in-depth quality analysis was performed. It consists of comparing the in-situ contour reconstruction against reference value in terms of dimensional accuracy and precision for the estimation of three different geometrical features: i) diameter of circular shapes, ii) side of squared shape, iii) angles of triangular shapes. This further evaluation was based on a robust minimum squared error fitting of identified contours.

4. EXPERIMENTAL SETUP

4.1 LPBF system and designed experiments

The experimental study was realized using a LPBF prototype system developed at the Department of Mechanical Engineering of Politecnico di Milano. The prototype system is equipped with an off-axis integrated high-resolution IDS camera (10 Mpixels) with a 25 mm lens placed as shown in Fig. 1.



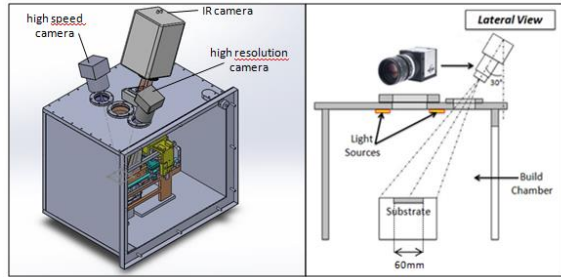


FIGURE 1. System setup. Top: front view of the prototype. Bottom-left: CAD scheme of the off-axis sensor installed on the prototype. Bottom right: scheme of the high-resolution camera disposition.

The laser used is a IPG YLR-300, a Ytterbium-doped yttrium aluminum garnet (Yb:YAG) laser source, with a maximum power of 250W and a wavelength of 1060nm.

During the printing processes, the building chamber is filled with argon, in order to reproduce an inert atmosphere and an over-pressure equal to 50 mbar is created to avoid the risk of oxygen contamination.

The prototype system was used to produce three builds:

Build 1: this build was realized to study the effect shape and laser scan angle on the image segmentation quality at different illumination conditions. Shape factor has two levels: cylinders of diameters $d=5$ mm and parallelepipeds with squared area of side $l=5$ mm. Scan angle factor has four levels: 0° , 45° , 90° and 135° . Each treatment was replicated twice. The 16 specimens were randomly located within the build area by filling a 4x4 regular grid.

Build 2 and Build3: They were realized to further investigate the sensitivity to illumination conditions and to characterize the in-situ dimensional error. These builds are two replicates of a latin-square plan with one factor, part shape, with three levels: cylinders of diameters $d=5$ mm, parallelepipeds with squared area of side $l=5$ mm, and isosceles triangular prism with base of height $h=6$ mm and angles equal to $67,38^\circ$ and $45,24^\circ$. In Build 2 and Build 3 the scan angle in the last layer was the same, i.e., 0° .

All the specimens in different builds were produced with default process parameters.

A checkerboard calibration of layerwise imaging was performed leading to an in-situ spatial resolution of $20 \mu\text{m}/\text{pixel}$.

Images were acquired before and after the laser scan of the last layer. A pre-processing step of

in-situ post-scan images was applied in order to enhance the segmentation quality for both the ACWE and LSE BFE algorithms. The post-scan image pre-processing operation consists of subtracting the average background intensity observed in the powder bed image acquired before laser scan and applying the absolute value to pixel intensities. This improves the gap between average intensities in foreground and background regions, making the region-based active contours methodology more effective.

4.2 Lighting system configurations

It is known that image segmentation and edge detection algorithms are strongly influenced by lighting conditions [11]. In industrial LBP systems, lighting configurations vary from one system to another. Moreover, different lighting configurations were investigated in previous studies devoted to layerwise imaging in LPBF, ranging from direction light sources placed in different locations to diffuse light conditions [2-6].

In this study, different illumination conditions were investigated by installing six LED strip lights as shown in Figure 2.

The six LED lights can be turned on one-at-a-time or simultaneously. When most of the light is not reflected towards the camera so-called *dark field illumination* condition is generated. This configuration is achieved when lights in the bottom region (A and B) are turned one, alone or simultaneously to vertical lights (L and R).

When the majority of light is reflected towards the camera, instead, a so-called *bright field illumination* condition is generated. This configuration is achieved when lights in the top region (C and D) are turned one, alone or simultaneously to vertical lights (L and R).

When multiple lights are turned on simultaneously e.g., double parallel (AD, BC, LR) or perpendicular lights (CL, CR, BL, BR), or more than two lights (CLR, BCR, BLR, BCL, BCLR) at a time, other illumination conditions can be generated as well, which do not strictly belong to the two aforementioned conditions. In this study, a total number of 24 illumination conditions were tested and compared.

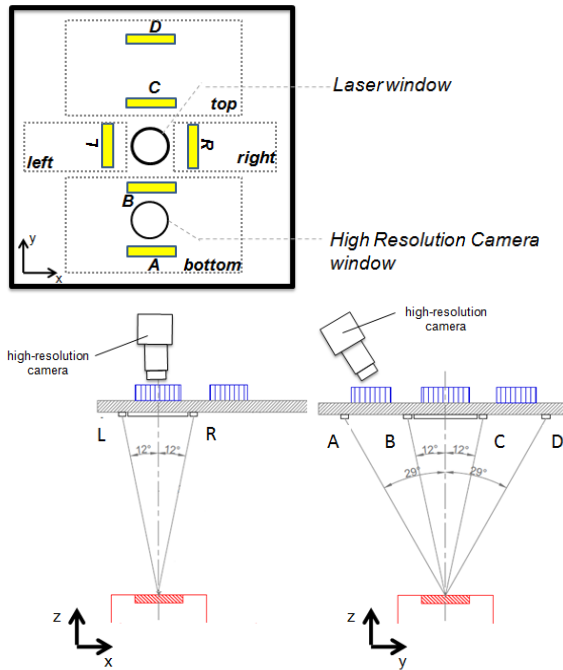


FIGURE 2. Scheme of the illumination system disposition.

For the reference measurements e.g., the ground truth reference for image segmentation evaluation and the reference standard for determination of accuracy, the ex-situ images was acquired through a Mitutoyo Quick Vision Active optical microscopy equipped with an 2.5X optic, with a spatial resolution of 1,9 $\mu\text{m}/\text{pixel}$.

5. RESULTS

5.1 Scan angle effect

Figure 3 shows one example of in-situ image acquired for the last layer of Build 2 (Figure 3 a), the corresponding ex-situ image acquired with the optical microscope (Figure 3 b) and the ground truth contours superimposed to the in-situ image (Figure 3 c). The scan angles applied to produce the last layer of each specimen are shown in Figure 3 b.

The Analysis of Variance (ANOVA) [12] on Dice index showed that for none of the considered illumination conditions neither the shape nor the scan angle were statistically significant at familywise confidence of 5%, with the only exception of lighting configurations AD and BD for which the scan angle resulted to have a significant effect. Both configuration AD and BD combined two horizontal lights parallel to the x-axis and they yielded a significantly lower segmentation quality in the presence of scan angle 90° , i.e., when the direction of scanned

hatches was perpendicular to the LED strip direction. However, all the illumination conditions that yielded the highest segmentation quality were robust to the scan angle factor.

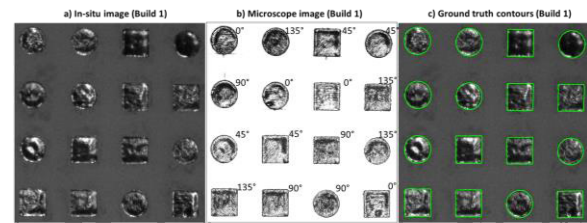


FIGURE 3. one example of in-situ image acquired for the last layer of Build 1 (a), the corresponding ex-situ image acquired with the optical microscope (b) and the ground truth contours superimposed to the in-situ image (c).

5.2 Screening of light configurations

Figure 4 shows the 95% confidence intervals for the Dice's index provided by the ACWE and LSE BFE methodologies applied to Build 2 and Build 3.

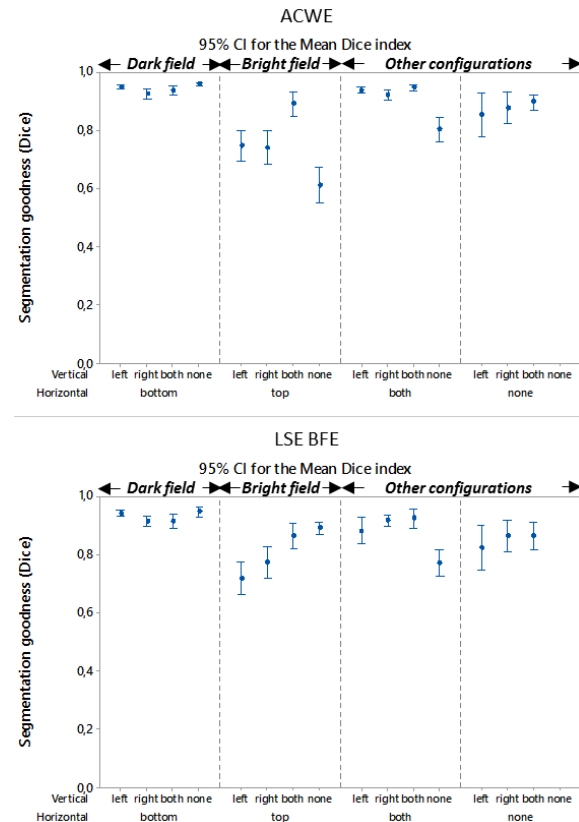


FIGURE 4. 95% confidence intervals for the Dice's index provided by the two analyzed methods

Figure 4 shows that dark field configurations yield the highest segmentation quality. For all these configuration the most of the light is not reflected towards the camera, which reduces the intensity in-homogeneity within the foreground region caused by the uneven surface, and hence it improves the foreground-background separation. Thus, in these cases the foreground appears homogeneously darker with respect to the background. Bright field configurations, instead, yield lower segmentation quality as they emphasize the foreground in-homogeneity caused by uneven surface patterns. Some configurations that do not belong to the two previous categories yield good segmentation quality as well. They include configuration where both top and bottom horizontal lights are present, combined with left, right or both vertical lights. These conditions reduce the foreground in-homogeneity caused by uneven surface patterns thanks to multisource lights.

The two illumination conditions that yielded the statistically highest segmentation quality according to the ANOVA analysis and Tuckey pairwise comparison tests at 95% confidence level were A and B, i.e., the two dark field configurations with single light sources.

Because of this, further in depth analysis of in-situ dimensional error was carried out for these two configurations only.

5.3 In-situ dimensional error characterization

Figure 5 shows the in-situ dimensional error estimated for different active contours methods and different geometrical features (diameter of a circular shape, side length of a square and angle of a triangular shape). The dimensional errors are expressed as percentage of the reference dimension. Table 1 and Table 2 shows the average error (bias) and the standard deviation of the error (uncertainty) for the compared conditions and for the two segmentation methods. The in-situ measurement bias is on average in the order of 4% and the uncertainty is in the order of $\sigma = 2-3\%$.

The in-situ dimensional measurements exhibit a negative bias for all the geometrical features. This can be mainly due to possible biases originated during in-situ camera calibration. For both illumination conditions A and B, there was no significant difference in terms of dimensional errors between the two segmentation algorithms. However, illumination condition B yielded a more robust result as the angle estimation error was not statistically different from the dimensional errors for the

other geometrical features, whereas in the presence of condition A, the angle reconstruction was significantly worst. In the presence of illumination condition B, a slightly higher build-to-build variability was observed.

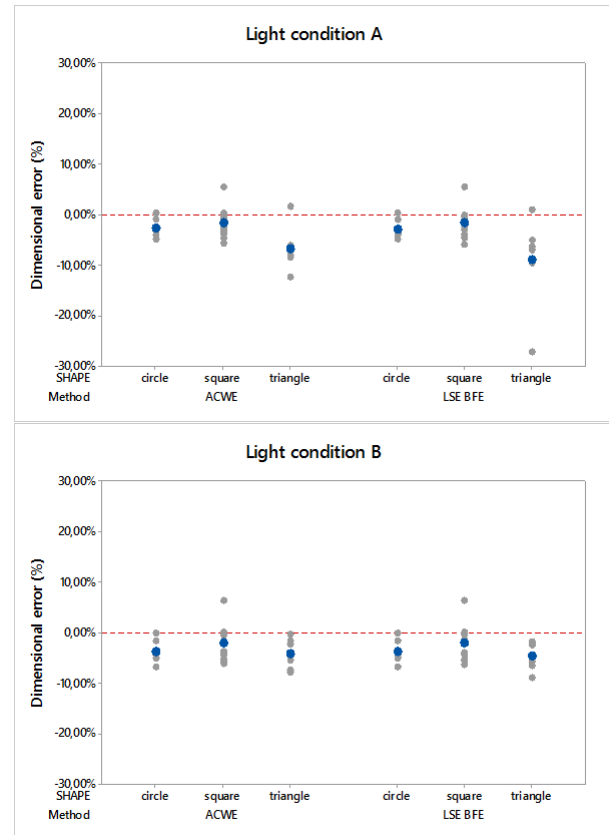


FIGURE 5 – single value plot of percentage difference between in-situ and optical microscope measurements

Table 1. difference of dimensional errors between in-situ and optical microscope measures – method ACWE

ACWE (Build 2)				
	Illumination condition A		Illumination condition B	
	Absolute error	Percentage error (%)	Absolute error	Percentage error (%)
Circle (diameter)	-143,73 μm (138,40 μm)	-2,86 (2,75)	-159,23 μm (136,868 μm)	-3,17 (2,72)
Square (side)	-34,35 μm (186,72 μm)	-0,67 (3,73)	-46,9 μm (211,92 μm)	-0,92 (4,23)
Triangle (angle)	-2,31° (2,59°)	-5,06 (5,7)	-1,39° (1,72°)	-3,06 (3,77)
ACWE (Build 3)				
	Illumination condition A		Illumination condition B	
	Absolute error	Percentage error (%)	Absolute error	Percentage error (%)
Circle (diameter)	-135,3 μm (78,65 μm)	-2,67 (1,55)	-215,54 μm (130,98 μm)	-4,25 (2,58)
Square (side)	-130,32 μm (84,43 μm)	-2,56 (1,66)	-160,8 μm (117,54 μm)	-3,16 (2,33)
Triangle (angle)	-3,76° (1,58°)	-8,32 (3,51)	-2,37° (1,26°)	-5,25 (2,84)

Table 2. difference of dimensional errors between in-situ and optical microscope measures – Method LSE BFE

LSE BFE (Build 2)				
	Illumination condition A		Illumination condition B	
	Absolute error	Percentage error (%)	Absolute error	Percentage error (%)
Circle (diameter)	-143,62 μm (138,31 μm)	-2,86 (2,75)	-159,02 μm (135,78 μm)	-3,16 (2,7)
Square (side)	-38,05 μm (188,01 μm)	-0,75 (3,76)	-46,48 μm (209,19 μm)	-0,91 (4,17)
Triangle (angle)	-2,36° (2,51°)	-5,18 (5,52)	-1,55° (1,21°)	-3,41 (2,66)
LSE BFE (Build 3)				
	Illumination condition A		Illumination condition B	
	Absolute error	Percentage error (%)	Absolute error	Percentage error (%)
Circle (diameter)	-139,55 μm (80,13 μm)	-2,75 (1,57)	-224,29 μm (133,45 μm)	-4,42 (2,62)
Square (side)	-135,31 μm (78,62 μm)	-2,66 (1,55)	-161,65 μm (123,05 μm)	-3,18 (2,43)
Triangle (angle)	-5,81° (5,57°)	-12,86 (12,36)	-2,54° (1,44°)	-5,63 (3,23)

6. CONCLUSIONS

The layerwise production paradigm of LPBF processes provides the opportunity to look at the part on a layer-by-layer basis during the entire process. This enables the possibility of identifying the contours of each printed slice to support the in-situ part quality characterization and 3D geometry reconstruction based on in-situ images. This study represents the first attempt to characterize the accuracy of in-situ image segmentation and slice contour detection. The analysis presented here show that accurate dimensional measurements can be achieved through adequate illumination conditions with a high-resolution camera (about 20 $\mu\text{m}/\text{pixel}$), reaching measurements errors in the lower than 5%.

Future developments will be aimed to investigating image processing and sensing solutions to further improve these performances. Moreover, the proposed settings will be used to characterize more complex shapes and the accuracy estimation will be integrated with thermal model, in order to compensate the effect of the shrinkage.

REFERENCES

- [1] Grasso M., Colosimo B.M., (2017), Process Defects and In-situ Monitoring Methods in Metal Powder Bed Fusion: a Review, *MeasSc and Tech*, 28(4), 1-25
- [2] Kleszczynski S, zur Jacobsmühlen J, Sehrt J T and Witt G 2012 Error detection in laser beam melting systems by high resolution imaging *Proc. of the Solid Freeform Fabrication Symp.*
- [3] Zur Jacobsmühlen J, Kleszczynski S, Witt G and Merhof D 2015 Elevated region area measurement for quantitative analysis of laser beam melting process stability *Instrum. Meas. Technol. Conf. I2MTC* pp 707–12
- [4] Kleszczynski S, zur Jacobsmühlen J, Reinartz B, Sehrt J T, Witt G and Merhof D 2014 Improving process stability of laser beam melting systems *Proc. of the Fraunhofer Direct Digital Manufacturing Conf.*
- [5] Foster, B. K., Reutzel, E. W., Nassar, A. R., Hall, B. T., Brown, S. W., & Dickman, C. J. (2015) Optical, layerwise monitoring of powder bed fusion. In *Solid Free. Fabr. Symp. Proc.*, 295-307.
- [6] Land W S, Zhang B, Ziegert J and Davies A 2015 In situ metrology system for laser powder bed fusion additive process *Proc. Manuf.* 1 393–403
- [7] Abdelrahman, M., Reutzel, E.W., Nassar, A.R., Starr, T.L., Flaw detection in powder bed fusion using optical imaging. *Addit. Manuf.*, 15 (2017), pp. 1-11, 10.1016/j.addma.2017.02.001
- [8] Li, C., Huang, R., Ding, Z., et al.: 'A level set method for image segmentation in the presence of intensity inhomogeneities with application to MRI', *IEEE Trans. Image Process.*, 2011, 20, (7), pp. 2007–2016
- [9] Chan T., Vese L. (1999) An Active Contour Model without Edges. In: Nielsen M., Johansen P., Olsen O.F., Weickert J. (eds) *Scale-Space Theories in Computer Vision. Scale-Space 1999. Lecture Notes in Computer Science*, vol 1682. Springer, Berlin, Heidelberg
- [10] K. H. Zou et al., "Statistical validation of image segmentation quality based on a spatial overlap index," *Acad. Radiol.*, vol. 11, no. 2, pp. 178–189, 2004.
- [11] Wu X., Gao G., LED light design method for high contrast and uniform illumination imaging in machine vision, 2018, *Applied Optics*, Vol. 57, No. 7
- [12] Montgomery DC. *Design and analysis of experiments*. New York: Wiley; 2017

In-situ areal inspection of powder bed for electron beam fusion AM system based on fringe projection

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Introduction

Additive manufacturing (AM) techniques, also referred to as three-dimensional (3D) printing, provide significant advantages over conventional subtractive manufacturing techniques, primarily in their ability to manufacture complex geometries with internal features by melting powder material layer-by-layer^[1]. As a consequence, AM technologies have developed greatly in both the industrial and academic fields. However, there are still many challenges in terms of part quality, such as surface roughness and performance of printed parts, stress deformation, defect detection, embedded material discontinuities, and reduction of inter-build variation^[2]. Powder delivery is a process that occurs thousands of times during build cycle of AM. During the melting process, cracks and pores and other discontinuities can occur within the printed objects due to the poor quality powder delivery. Hence the implementation of an effective in-situ detection approach for assessment of delivery quality could be an essential tool to improve part precision and to enhance product quality^[3].

Consequently the measurement task is to assess the powder bed for defects such as ridges, scores and areas deficient in powder. This task is difficult using photographic techniques due to poor contrast for example. Therefore, it is essential to investigate an inspection method that is full field, high speed, high accuracy and has a large field of view (FOV). The fringe projection technique has been widely studied for a number of years both the industry and academia primarily due of its advantages of, full-field, high speed, high accuracy, low cost and large field of view. These core advantages suit the requirements for the in-situ inspection of the AM process, therefore, fringe projection technique is adopted in the present study.

This paper presents an in-situ inspection technique based on fringe projection quantitative imaging for full-field 3D shape measurement of the powder bed in an electron beam fusion machine. The measurement task is to measure in both the x,y plane and in the z plane. This allows the assessment of defects in the planar direction and the out of plane direction. To facilitate quantitative measurement an accurate system calibration approach is initially investigated by using a polynomial calibration technique to obtain the system calibration parameters in both vertical and lateral directions. Secondly, a surface-fitting algorithm is investigated to reduce phase error and random noise to improve measurement accuracy. A phase-shifting algorithm and an optimum three-fringe number selection method^[4] is employed to calculate wrapped and absolute unwrapped phase maps accurately. Finally, the proposed in-situ inspection system has been built on a prototype powder delivery system and implemented on a prototype Ebeam AM machine (under vacuum) and areal inspection of the powder bed has been demonstrated in both cases.

Measurement Principle

In situ the inspection system is fixed on external structure of the AM machine and monitors the powder bed through two glass ports consisting of a composite lead and soda glass window. It consists of a CCD (charge-coupled device) camera and a DLP (digital light processing) projector. The position of the projector and the camera is fixed with the angle between the optical axes of circa 30 degrees. The inspected powder surface is at the intersection of the axes. During the manufacturing process, following the layer of powder is dispensed from the powder hopper. Sinusoidal fringe patterns are generated

by a computer and projected onto the surfaces of the powder through the projector. The deformed fringe patterns are captured by the camera via a second port. The geometry information of detected surface can be obtained after system calibration.

The principle of the fringe projection technique is based on triangulation [5]. In order to obtain geometry information, the spatial relationship between the DLP projector and CCD camera should be determined, as illustrated in Figure 1. The sinusoidal fringe patterns generated by software are projected on to the test surface. The fringe patterns are deformed due to part geometry, with respect to the height information and the deformed fringes are captured by the camera. Phase information is computed from the captured deformed fringe patterns. After system calibration, 3D shape data can be obtained from the phase information.

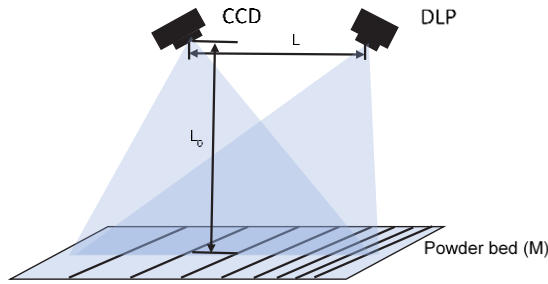


FIGURE 1. Schematic of fringe projection system

The geometric relationship of the projector and the camera can be represented by a mathematical relationship between the absolute phase map and depth data [6] as follows:

$$Z = \frac{L_0}{\frac{2\pi L_0^2 L \cos \theta}{P_0 \Delta \phi(x, y) (L_0 + x \cos \theta \sin \theta)^2} - \frac{L \cos \theta \sin \theta}{L_0 + x \cos \theta \sin \theta} + 1} \quad (1)$$

where Z is the height value relative to reference plane M . L is the distance between the CCD camera and the DLP projector. $\Delta \phi$ is the absolute unwrapped phase difference between the measured surface and the reference surface M . L_0 is the working distance from camera to the reference surface M . θ is the angle between the optical axes of the projector and the camera and P_0 is the period of the projected fringe pattern on a virtual plane. Therefore, height value can be calculated with the phase information and system parameters.

System calibration

System calibration establishes the relationship between the depth information and phase data, and the relationship between spatial position of a selected point in world coordinate system and the corresponding pixel position in camera coordinate system, these are referred to as depth calibration and transverse calibration, respectively.

• Depth calibration

It is hard to directly obtain the system parameters L , L_0 , P_0 for depth calibration as shown in Equation 1. In fact, by using the Taylor series expansion [7], Equation 1 can be transformed into a polynomial function

$$Z_r(x, y) = \sum_{n=0}^N a_n(x, y) \Delta \phi(x, y)^n \quad (2)$$

where a_n , a_{n-1} , a_2 , a_1 are sets of coefficients containing the system parameters. Based on the reference plane M in figure 1, a reference coordinate system can be built up. The method of depth calibration is to move a calibration surface (in the present case, a certified marked ceramic tile) to a series of known depth distance. At each position, depth is measured by an independent length measurement interferometer from Renishaw (Model: ML10) and phase information is calculated by projecting fringe patterns onto the calibration board. At the same time the texture images are captured by the camera at each position. Consequently, the geometric relationship of the camera and the projector can be determined.

• Transverse calibration

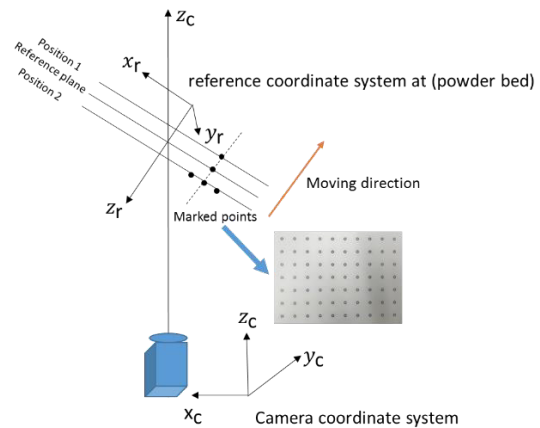


FIGURE 2. Schematic view of transverse calibration using the certified marked ceramic tile marked with precision ring artefacts.

Transverse calibration seeks to determine the relationship between the pixel position of camera coordinate system and the corresponding point position in the world coordinate system. Figure 2 shows the schematic of the transverse calibration. During calibration, the calibration tile is moved by a transfer stage, the path of the marked points is a curve in the camera coordinate system, this is due to the distortion of the camera lens. Therefore, the relationship between x value and z value and relationship between y value and z value can be expressed with Equation 3 and Equation 4 respectively, which is quadric.

$$X_r(x, y) = a_0(x, y)Z_r^2 + b_0(x, y)Z_r + c_0(x, y) \quad (3)$$

$$Y_r(x, y) = a_1(x, y)Z_r^2 + b_1(x, y)Z_r + c_1(x, y) \quad (4)$$

where $a_0, b_0, c_0, a_1, b_1, c_1$ are the coefficients of the quadric in the reference coordinate system. X_r, Y_r are the coordinate value in the reference coordinate system which is transferred by a homography matrix from the corresponding pixel positions in the camera coordinate system [8]. Z_r is the distance which is measured by the independent interferometer. After recording a series of known distance positions and the corresponding phase information, the polynomial coefficients of Equation 3 and 4 can be calculated by the least-squares algorithm. The relationship between reference coordinate system and camera coordinate system can then be determined by this approach.

• Surface fitting

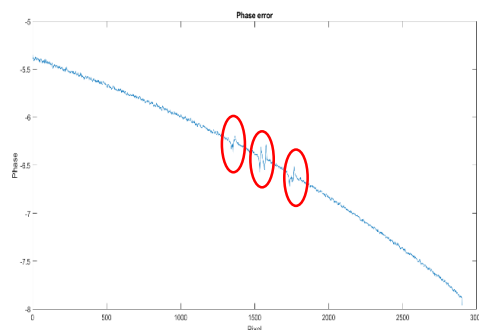


FIGURE 3. The impact of black circle ring results in phase error

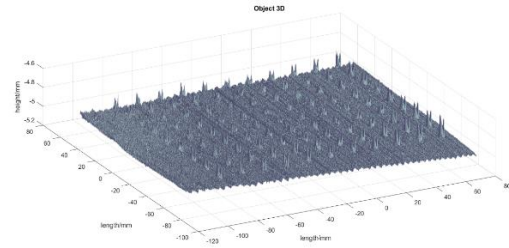


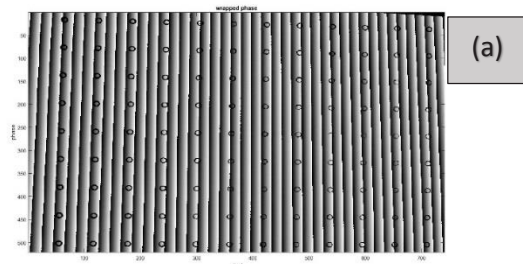
FIGURE 4. The impact of black circle ring results in measurement error

Due to the use of the calibration board which is marked with black circle rings for locating pixel positions, the presence of the rings impacts on the quality of fringe patterns, which results in phase error and measurement error, as demonstrated as in Figure 3 and Figure 4. A curve fitting algorithm approach was implemented to solve this issue. The modulation of the wrapped phase is calculated as demonstrated in Equation 5, in the figure the ring effects are clear. However by setting a threshold value, the outliers and the valid points can be separated, because the modulation of outliers is lower than the threshold value.

$$M = \frac{2}{N} \times \sqrt{\left[\sum_{n=0}^{N-1} I_n \sin\left(\frac{2\pi n}{N}\right) \right]^2 + \left[\sum_{n=0}^{N-1} I_n \cos\left(\frac{2\pi n}{N}\right) \right]^2} \quad (5)$$

where M is modulation, N is phase shifting steps, n is captured image sequence, I_n is the intensity of captured images. Therefore, the outliers which are removed, as shown in Figure 5(a). Unwrapped phase map is analysed from the rest of the wrapped phase data by using the optimum 3-frequency selection algorithm, as shown in Figure 5(b).

In order to fill in the invalid points, a quintic polynomial fitting equation was investigated to match the unwrapped phase data. Compared with the original unwrapped phase, the fitting data are processed uniformly which can suppress the influence of random noise and can improve the resolution and the accuracy of vertical direction.



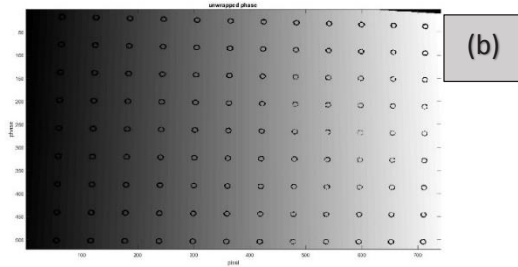


FIGURE 5. Removed outliers from wrapped phase map and unwrapped phase map (a)
 Wrapped phase without the outliers (b)
 unwrapped phase without the outliers

Experiments

In order to test the developed inspection system, experiments are carried out to verify the feasibility and validity of the proposed technique. A prototype measurement system was developed to measure 3D shape errors of a powder bed. The hardware consisted of a computer, a CCD camera and a projector. The CCD camera was an up to date industrial camera (model evo12040MBGEB) from SVS with a resolution of 3016x4016 pixels which can support external and internal trigger models. The projector was an industrial digital projector (light crafter, model 4500) with a resolution of 912x1140. The focal distance of the camera lens was 25mm. Twenty-four sinusoidal fringe patterns having optimum fringe numbers of 100, 99 and 90 were generated by software and sequentially projected onto the inspected surface through the projector. Following determination of the vertical parameters of a_n and transverse parameters of $a_0, b_0, c_0, a_1, b_1, c_1$ using the calibration method described above, the 3D shape of the powder surface was measured by the system.

To evaluate the accuracy of the developed 3D measurement system, a calibration board was placed on a known position which was measured by an interferometer with a resolution of 0.01 μm . The plate was positioned between -2.5mm and 2.5 mm with respect to the reference plane as shown the measurement depth profile results in Figure 6. The measured distance obtained by interferometer was the benchmark value, the measured average distance detected by the inspection system, the absolute error between the measurement results and the ideal value, and the standard deviation of across surface are listed in Table 1. A photograph of a series of ceramic slip gauges are shown

in Figure 7(a) and these were measured with proposed method as illustrated in Figure 7(b). The measured results obtained by the inspection system were compared to the standard step, as listed in Table 2. The results showed the system can achieve vertical resolution below 20 micrometers, with a standard deviation of 15.8 micrometers.

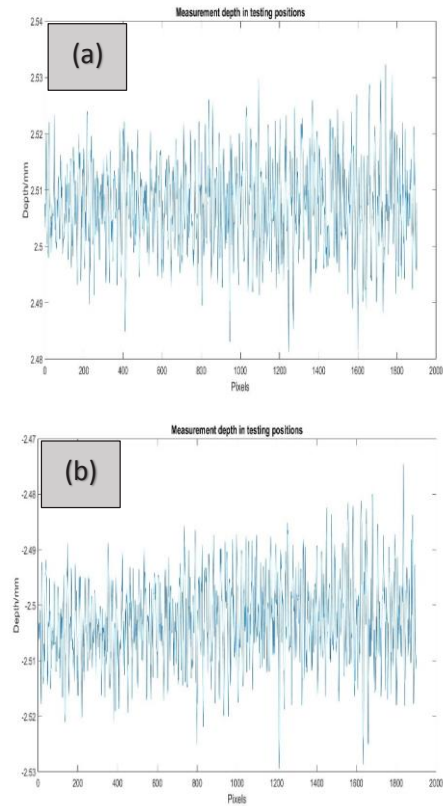


FIGURE 6. Measured distance along one row near the middle of the ceramic tile, X axis represents the pixel positions, vertical axis is the reconstructed depth of the surface (a) $z=2.5$ (b) $z=-2.5$

Table1. Measured distance compare with interferometer measurement

Interferometer /mm	Measured average distance /mm	Absolute error/mm	Standard deviation /mm
2.5003	2.5072	0.0069	0.0158
-2.5008	-2.5029	0.0021	0.0127

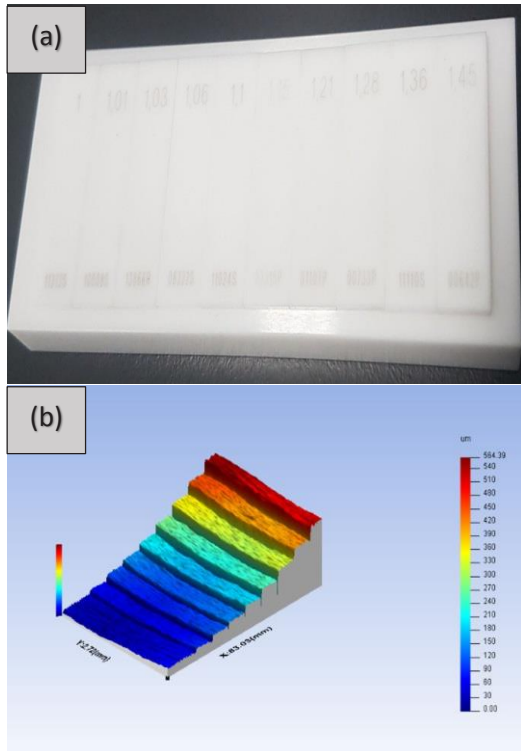


FIGURE 7. Illustration of the standard ceramic step and measured 3D shape data(a) Photograph of the standard ceramic step (b) the measured 3D shape

Table2. The experimental results on the measured step (Unit: μm)

Standard distance/ μm	Measurement distance/ μm	Absolute error/ μm
10	8.1	1.9
20	19.3	0.7
30	31.7	1.7
40	37.6	2.4
50	50.5	0.5
60	62.7	2.7
70	75.1	5.1
80	86.9	6.9
90	102.0	10.2

The flat white marked ceramic tile was measured by the proposed fitting calibration algorithm as shown in Figure 8. Figure 8(a) shows the measured data ignoring the impact of the black circle rings and Figure 8(b) shows the improved threshold results. The proposed calibration method clearly solves the impact of black circle rings.

An actual measurement captured by the powder bed system is shown in Figure 9. In this example excessive powder has been delivered to the bed due to a broken tooth on the powder rake. In addition it is possible discern the out of plane part geometry.

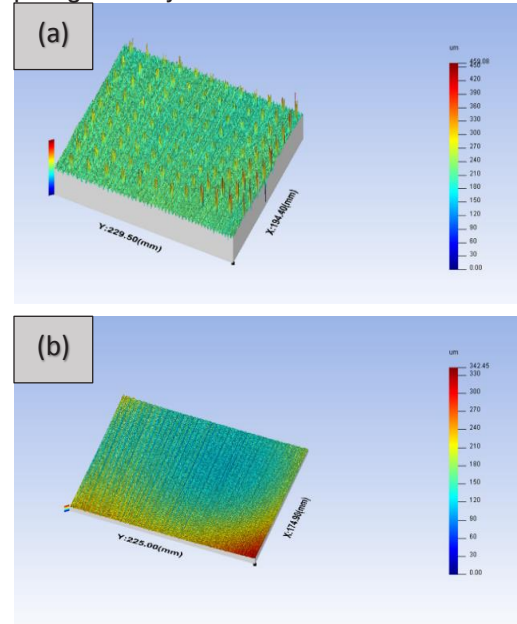


FIGURE 8. 3D shape measurement results of a flat plate (a) 3D shape measurement results with impact of black circle ring (b) 3D shape measurement results with proposed method

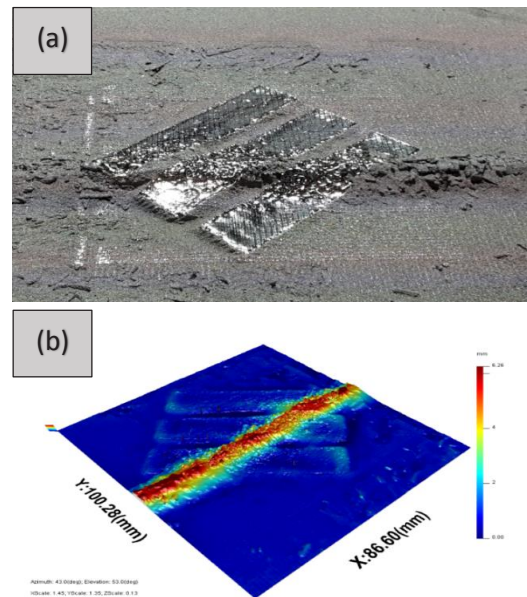


FIGURE 9. Excessive powder delivery on top of partially build parts (a) Photograph of tested powder (b) 3D results of tested powder

Conclusions

In this paper, an in-situ monitoring technique is investigated to inspect powder bed of electron beam fusion system by using a fringe projection technique. A circle ring calibration board was used to calibrate system parameters. A novel surface fitting algorithm was developed to improve measurement accuracy and vertical resolution. The problem of the inaccuracy of the phase information from circle ring area was solved. The actual experimental data show the validity and feasibility of the proposed inspection technique.

Reference

- [1] Townsend A, Senin N, Blunt L, Leach RK, Taylor JS. Surface texture metrology for metal AM: a review. *Precision Engineering*. 2016 Oct 31; 46:34-47.
- [2] Everton SK, Hirsch M, Stravroulakis P, Leach RK, Clare AT. Review of in-situ process monitoring and in-situ metrology for metal AM. *Materials & Design*. 2016 Apr 5; 95:431-45.
- [3] Martin KF. A review by discussion of condition monitoring and fault diagnosis in machine tools. *International Journal of Machine Tools and Manufacture*. 1994 May 1; 34(4):527-51.
- [4] Zhang Z, Towers CE, Towers DP. Time efficient color fringe projection system for 3D shape and color using optimum 3-frequency selection. *Optics express*. 2006 Jul 10;14(14):6444-55.
- [5] Xie Z, Wang J, Zhang Q. Complete 3D measurement in reverse engineering using a multi-probe system. *International Journal of Machine Tools and Manufacture*. 2005 Oct 1; 45(12-13):1474-86.
- [6] Zhang Z, Huang S, Meng S, Gao F, Jiang X. A simple, flexible and automatic 3D calibration method for a phase calculation-based fringe projection imaging system. *Optics Express*. 2013 May 20; 21(10):12218-27.
- [7] Zhang Z, Huang S, Meng S, Gao F, Jiang X. A simple, flexible and automatic 3D calibration method for a phase calculation-based fringe projection imaging system. *Optics express*. 2013 May 20; 21(10):12218-27.
- [8] Zhang Z. A flexible new technique for camera calibration. *IEEE Transactions on pattern analysis and machine intelligence*. 2000 Nov; 22(11):1330-4.

REAL-TIME OBSERVATION OF SELECTIVE LASER MELTING OF WC-Co CEMENTED CARBIDE

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INTRODUCTION

Selective laser melting (SLM) is one of the additive manufacturing techniques producing solid structures directly from three-dimensional design data. In SLM, powder is spread in a thin layer and the powder particles are subsequently melted together by a laser beam. By repeating these processes, complex-shape components can be fabricated [1].

WC-Co cemented carbide is known for its high hardness and toughness and used for cutting tools, punching molds, rock drill tips and wear resistant parts. This material is generally produced by a powder sintering method from the mixed powder of ceramic (WC) and metal (Co). The conventional powder sintering method requires high temperature, high pressure, long reaction time and post finishing process. SLM process can produce parts without such requirements. However, early attempts to apply SLM to WC-Co cemented carbide were not successful due to pores and cracks [2, 3, 4]. The numbers of cracks and pores depend on processing conditions such as laser power, spot diameter, scan speed and linear energy density (LED) [5, 6]. LED is defined by

$$LED = \frac{P}{v} \text{ [J/mm]}$$

(where P is laser power [J], v is scan speed [mm/s]). LED is a factor for energy input to a powder layer in the unit length by a laser beam [7]. Observation of SLM process and understanding of the phenomena are essential for optimization of process parameters [8, 9, 10]. In this study, we constructed a real-time observation system of SLM process and observed the behavior of molten WC-Co cemented carbide at the laser-interaction zone.

EXPERIMENTAL

We scanned a laser beam over a layer of WC-Co powder mixture on a WC-Co bulk plate. We varied scan speed and laser power fixing LED and confirmed the shape of beads by a laser microscope. And real-time observation of the laser-interaction zone was carried out by a high-speed camera and a laser illumination.

We used a single-mode fiber laser (JL-SP0178, SPI Lasers) and wavelength and beam diameter were 1070 nm and 30 μm , respectively. Scan speed and laser power were set to 25 mm/s - 25 W, 50 mm/s - 50 W, 75 mm/s - 75 W and 100 mm/s - 100 W, while the LED was fixed to 1 J/mm. We observed the shape of beads and measured the cross-sectional profiles of the samples at the center of the laser-scanned tracks by a laser microscope (LEXT OLS4500, OLYMPUS CO.)

Figure 1 shows the schematic of the observation system. The laser-interaction zone was captured with a high-speed camera (FASTCAM SA3, Photron Ltd.). Frame rate and shutter speed were set to 10000 fps and 20 μs , respectively. We used a laser illumination (Cavilux HF, Cavitax Ltd.) with 20 ns pulse duration and 810 nm wave length. An 810 nm bandpass filter was used to exclude the influence of scattered light of the laser and emission from the molten pool.

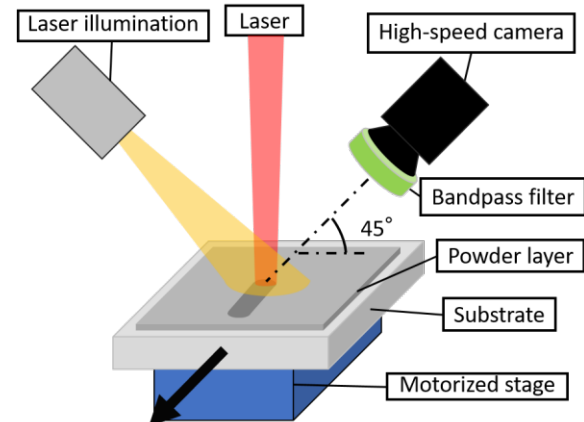


FIGURE 1. Schematic of real-time observation system of SLM process.

With ordinary illumination light, real-time observation of the molten pool is difficult because of the influence of scattered light of the laser and emission from the molten pool (Fig. 2(a)). Laser illumination emits high-intensity single-wavelength light in synchronization with exposure of the high-speed camera and the high speed camera receives only reflection of laser illumination light through the bandpass filter, which enables real-time observation of the molten pool (Fig. 2(b)).

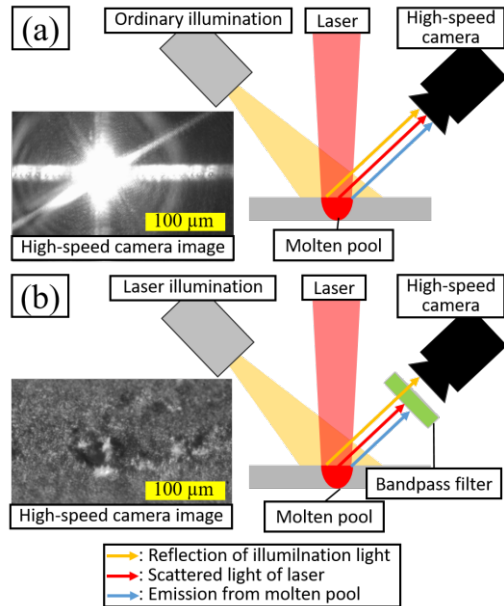


FIGURE 2. Schematic of real-time observation with (a) ordinary illumination and (b) laser illumination.

The layer of WC-Co powder (layer thickness: 30 μm) was applied on the WC-Co plate. Mixture ratio of the powder was 90 wt.%WC - 10 wt.%Co and diameters of each powder particles were 5 μm (WC: WWI01PB, Co: COE03PB, Kojundo Chemical Lab. Co.). Figure 3 shows microscope images of each powder.

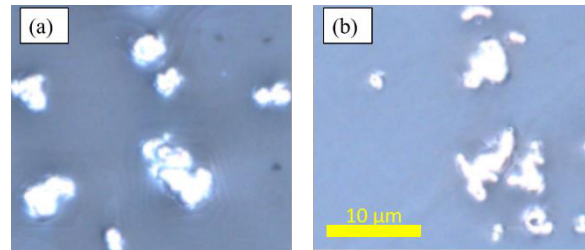


FIGURE 3. Microscope images of (a) WC powder, (b) Co powder.

RESULTS AND DISCUSSION

Microscope observation

Figure 4 shows laser-microscope images of the laser-scanned areas and cross-sectional profiles at the center of laser-scanned tracks. The beads were discontinuous and spheroidized at 25 mm/s - 25 W and 50 mm/s - 50 W (Fig. 4(a), (b)). On the other hand, the beads were continuous at 75 mm/s - 75 W and 100 mm/s - 100 W (Fig. 4 (c), (d)). Figure 5 shows the average height at the center of beads (Errorbar : arithmetic average roughness)

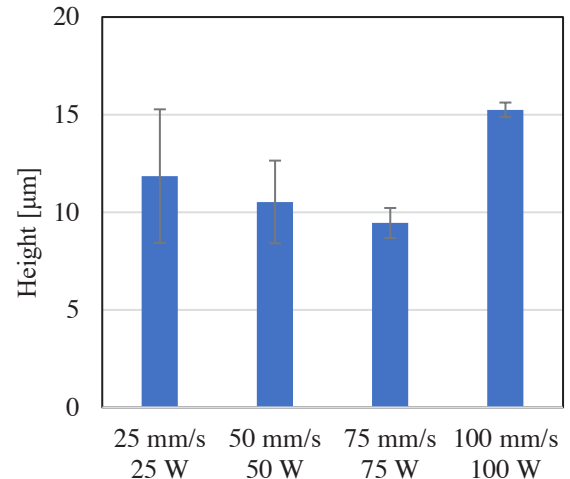


FIGURE 5. The average height at the center of the beads.

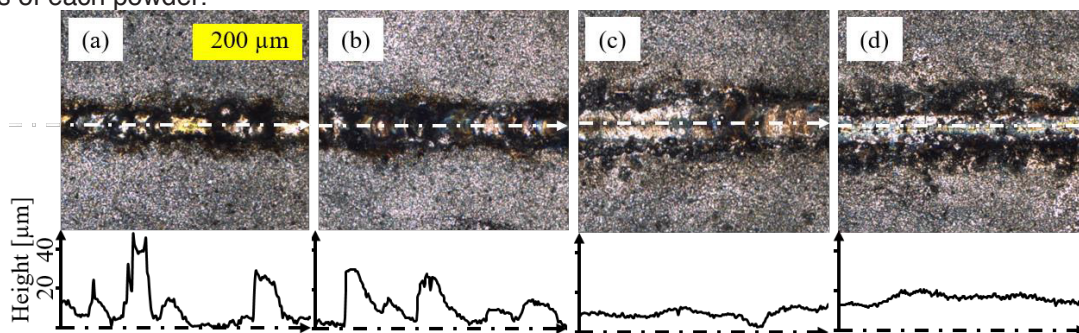


FIGURE 4. Laser-microscope images of the laser-scanned areas and cross sectional profiles at the center of laser-scanned trajectories at (a) 25 mm/s - 25W, (b) 50 mm/s - 50 W, (c) 75 mm/s - 75 W and (d) 100 mm/s - 10

Figure 6 shows the laser-microscope image of the laser-scanned area and cross-sectional profile of the beads perpendicular to laser-scan direction at 100 mm/s – 100W. WC-Co powder mixture was sintered maintaining the shape of powder layer at the edge of the beads. This result indicates that the powder mixture adjacent to the molten pool was heated by radiation and heat transfer from molten pool and Co particles in powder mixture melted and solidified without forming molten pool (Fig. 7).

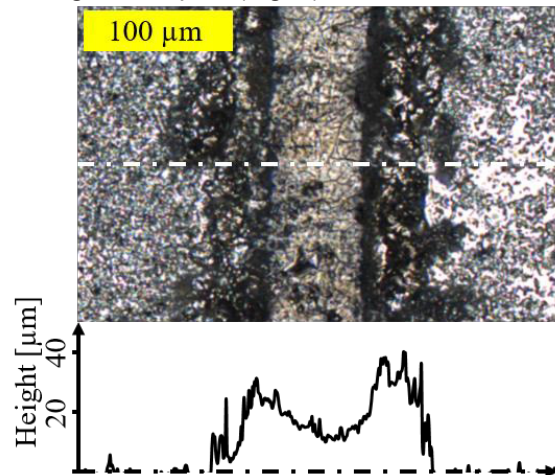


FIGURE 6. Laser-microscope image of laser-scanned areas and cross-sectional profile of the beads perpendicular to laser scan direction at 100 mm/s – 100 W.

Real-time observation

Figures 8 and 9 show high-speed camera images of the laser-interaction zone at 25 mm/s - 25 W. At first, molten cemented carbide formed droplets (Figs. 8(a), 9(a)). Next, droplets coalesced together to form a bigger droplet due to surface tension (Figs. 8(b, c, d)) or droplets sputtered due to recoil (Figs. 9(b, c)). These phenomena were also observed at 50 mm/s – 50 W.

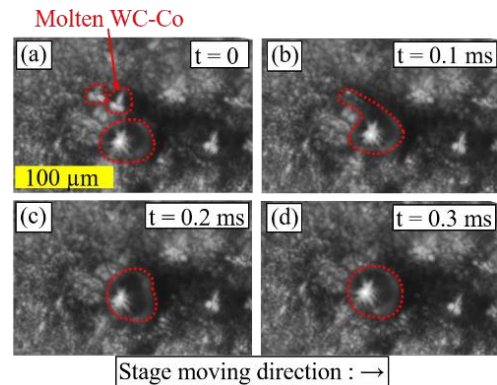


FIGURE 8. High-speed camera images of droplets coalescing together at 25 mm/s - 25 W.

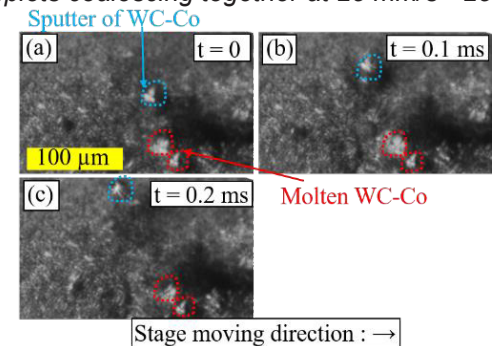


FIGURE 9. High-speed camera images of sputtering droplet at 25 mm/s - 25 W.

Figure 10 shows high-speed camera images of the laser-interaction zone at 75 mm/s - 75 W and 100 mm/s – 100 W. The molten pool was stable and formed continuous beads at high scan speed.

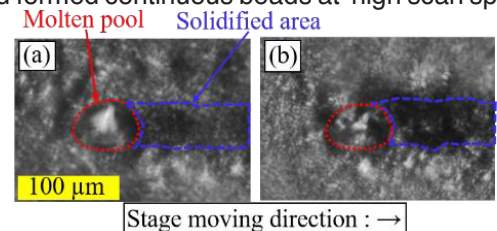


FIGURE 10. High-speed camera images at (a) 75 mm/s – 75 W and (b) 100 mm/s - 100 W.

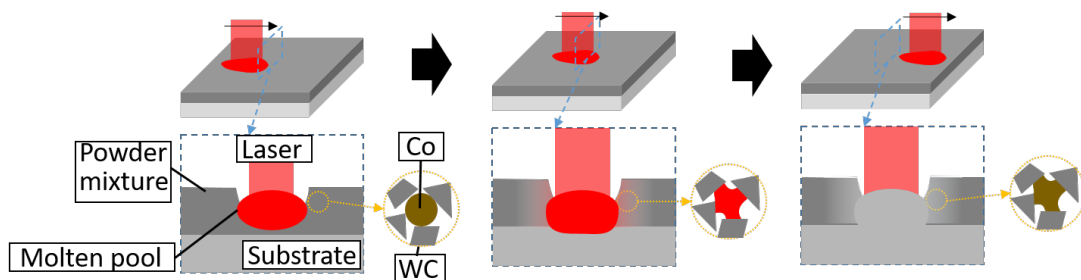


FIGURE 7. Schematic of melting and solidification phenomena of Co particles in WC-Co powder mixture adjacent to molten pool

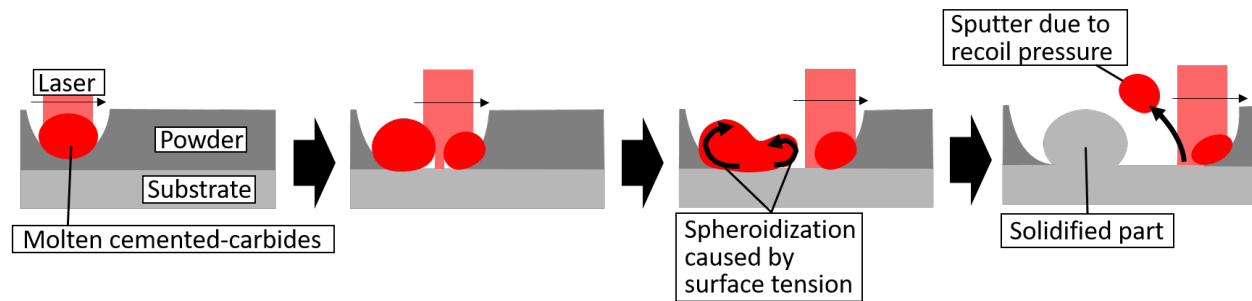


FIGURE 11. Schematic of melting and solidification phenomena at low scan speed.

These results indicate that the speed of spheroidization of molten WC-Co cemented carbide was higher than the scan speed at lower scan speed. Thus, molten powder formed droplets, not continuous molten pool, and the droplets formed discontinuous beads (Fig. 11).

CONCLUSIONS

We carried out real-time observation of the laser-interaction zone by a high-speed camera to investigate the effect of scan speed on laser-interaction zone. We scanned a laser beam over a layer of WC-Co powder mixture on a WC-Co plate. We varied the power and scan speed of laser fixing LED and confirmed the shape of the beads by a laser microscope.

Molten WC-Co cemented carbide formed droplets due to the surface tension and the solidified droplets formed discontinuous and spheroidal beads at low scan speed. On the other hand, molten pools were stable and the solidified molten pool formed continuous beads at high scan speed.

REFERENCES

- [1] Kruth JP, Mercelis P, Vaerenbergh JV, Froyen L, Rombouts M. Binding mechanisms in selective laser sintering and selective laser melting. *Rapid Prototyping Journal*. 2005; 11: 26-36
- [2] Gu D, Meiners W. Microstructure characteristics and formation mechanisms of in situ WC cemented carbide based hardmetals prepared by Selective Laser Melting. *Material Science and Engineering A*. 2010; 527: 7585-7592.
- [3] Uhlmann E, Bergmann A, Gridin W. Investigation on Additive Manufacturing of Tungsten Carbide-cobalt by Selective Laser Melting. *Procedia CIRP*. 2015; 35: 8-15.
- [4] Domashenkov A, Borbély A, Smurov I. Structural modifications of WC/Co nanophased and conventional powders processed by selective laser melting. *Materials and Manufacturing Processes*. 2017; 32: 1-93-100.
- [5] Scipioni B U, Wolfer A J, Matthews M J, Delplanque J P R, Schoenung J M. On the limitations of Volumetric Energy Density as a design parameter for Selective Laser Melting. *Material and Design*. 2017; 113: 331-340.
- [6] Williams J D, Deckard C R. Advances in modeling the effects of selected parameters on the SLS process. *Rapid Prototyping Journal*. 1998; 4: 2-90-100
- [7] Gu D, Chang F, Dai D. Selective Laser Melting Additive Manufacturing of Novel Aluminum Based Composites With Multiple Reinforcing Phases. *Journal of Manufacturing Science and Engineering*. 2016; 138: 021004-1-11.
- [8] Lauri T, Heidi P, Olli N, Antti S. Correlation between Pyrometer Monitoring and Active Illumination Imaging of Laser Assisted Additive Manufacturing of Stainless Steel. *ICALEO*. 2011; 404: 196-204.
- [9] Okunkova A A, Peretyagin P Y, Podrabinnik P A, Zhirnov I V, Gusarov A V. Development of Laser Beam Modulation Assets for the Process Productivity Improvement of Selective Laser Melting. *Procedia IUTAM*. 2017; 23: 177-186
- [10] Zhao C, Fezzaa K, Cunningham R W, Wen H, Francesco D C, Chen L, Anthony D, Sun T. Real-time monitoring of laser powder bed fusion process using high-speed X-ray imaging and diffraction. *SCIENTIFIC REPORTS*. 2017; 7: 3602.

Packing Characteristics of Thin Metal Powder Beds using High Resolution Areal Topography and Gravimetric Analysis

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Preliminary results regarding the packing fraction of thin layers of spherical metal powder are analyzed using state-of-the-art non-contact areal topography and gravimetric analysis. The thin powder beds are deposited using a simple shear powder press and lightly sintered in place for ex-situ measurement. The height distribution of powder beds using Ti64 powder in the 15-45 μm and 45-106 μm particle size distributions are made using state-of-the-art white light interferometry. This method represents a novel approach to characterizing the packing characteristics of AM powder, as well as the role of the substrate/powder interface.

I. INTRODUCTION

Powder Bed Fusion(PBF) is based on the repeated spreading and melting of thin layers of metallic powder.^{1,2} The uniformity of these layers can significantly affect the properties of the final component, as powder voids formed during spreading can seed defects in the finished part.^{1,3,4}

The feedstock powder must have properties which enable the spreading of dense, homogenous layers, with minimal voids and segregation.⁵ These properties must be maintained throughout the powder lifetime, which can include recycling, handling and extended storage periods. Despite the importance of powder spreadability, no universal description or standard for quantitative spreadability exists.⁴ Currently, AM powder is characterized by tests which capture some, but not all of the spreading-related properties; including morphology, granulogy, flowability, and bulk packing characteristics. While new, AM-specific standards are being proposed, no metric currently exists to quantitatively determine the relationship between the thin powder bed, the form of the underlying substrate, the local variations in powder height and packing density.^{2,6-8}

This feature can be partially attributed to the lack of large area characterization techniques which can provide particle-scale resolution. While discrete element models are offering new insights into the spreading dynamics of metal powder, calibrating the constitutive properties of the numerical inputs remains challenging.⁹ In some instances, custom powder bed systems have been

developed which allow more detailed analysis of powder bed, including gravimetric analysis and in-situ powder sampling.^{5,10-13} Recently, an in-situ powder bed height characterization technique has been demonstrated by workers at LLNL.¹⁴ Besides the productivity argument, powder packing can affect the optical penetration depth and absorptivity during laser PBF as well as electrostatic charging during electron beam PBF.¹⁵⁻¹⁹

Ultimately, developing robust, easy-to-interpret spreading and packing metrics will accelerate AM technology development. In the following, a method based on simple tooling, vacuum sintering, gravimetric analysis and non-contact areal topography is described. The resulting data is used to calculate the packing fraction of thin powder beds, highlighting the importance of solid-particle contacts in thin powder beds.

1. Packing Fraction of thin powder beds

The behaviour of powder in motion depends on the particle-particle and particle-solid cohesive forces, environmental interactions, applied stress and recoater speed.^{1,3,6} This implies that powder spreadability must be defined with respect to a specific powder distribution system, which includes variations in layer heights, temperatures, atmospheres and spreading mechanism. In other words, the packing of individual metal powder layers during PBF is a combined function of the feedstock as well as the proprietary hardware.^{2,20}

The packing fraction, ϕ [A.U.], of an arbitrary powder bed is defined by the ratio of the bed density, ρ_{bed} , over the equivalent solid density ρ_{solid} .^{5,21}

$$\phi = \frac{\rho_{bed}}{\rho_{solid}} \quad (1)$$

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Since the bed mass is defined by the solid particles, the packing fraction can also be defined according to:

$$\phi = \frac{\nu_{solid}}{\nu_{bed}} \quad (2)$$

where ν_{bed} represents the total volume of the porous bed, $\nu_{bed} = \nu_{void} + \nu_{solid}$, with ν_{void} and ν_{solid} being volume of the voids and solid, respectively. Assuming the bed is isotropically distributed over the area A , Eq. 2 can be also be defined as:

$$\phi = \frac{A * z_{solid}}{A * z_{bed}} = \frac{z_{solid}}{z_{bed}} \quad (3)$$

where z_{solid} is the equivalent height of the consolidated powder, and z_{bed} is the height of the powder bed itself.

For beds which are much thicker than the median particle diameter, D_{50} , Eq. 3 is easy to interpret, since the discrete nature of the particles make a negligible contribution to the overall height. This is generally the case when defining properties such as apparent or tapped density.

In PBF processes, the gap between the solid substrate and the recoater, z_{gap} is the same magnitude as the particle diameter. This makes a precise definition of bed thickness, and thus packing fraction, ambiguous. One simple solution is to assume z_{bed} is equivalent to the build table displacement. This approach ignores the consolidation effect and assumes the substrate is also flat and planar with respect to the recoater over the entire build.²²

Formally, when a characteristic dimension of the powder bounding volume is less than 10 times the particle size, the wall will have an ordering effect on the random packing.²¹ The particles in direct contact with the wall will form a region of comparably low packing due to the relative curvature between the surface and particles.²¹ How ordering effects such as periodic surface features are communicated through the powder layer is still not well understood.^{5,20}

Intuitively, the packing fraction of a single layer of powder is bounded by $0 \leq \phi \leq \phi_{tap}$, where the lower bound is defined by $z_{gap} < D_{10}$. Assuming the distribution method provides sufficient kinetic energy to settle the powder, the upper bound is defined by $z_{gap} \gg D_{90}$.

In the following, an experimental method is described which can deposit a thin powder bed. In principle, this method can be extended to measure how the packing fraction evolves as a function of both the spreading method and the powder itself.

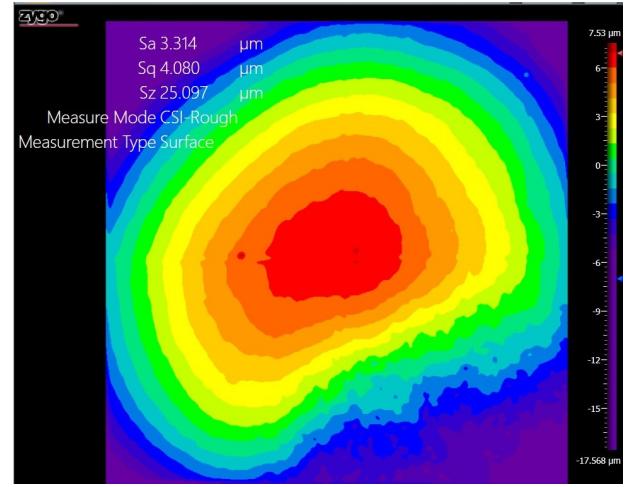


FIG. 1: Surface topology of Ti64 substrate after planarization, with each color representing $1\mu\text{m}/\text{div}$

II. METHODS AND MATERIALS

The 50x50x1.5 mm Ti64 solid substrates were laser cut (Baoji Magotan Nonferrous Metals, Shaanxi, China) and manually ground using 240-320-400 grit SiC abrasive paper. The topological surface profile of a substrate after planing are shown in Fig. 1

The substrates were etched for 2 minutes in a modified Krolls reagent of $[\text{HF}:\text{HNO}_3:\text{H}_2\text{O}] = [1:2:10]$ to remove the mill finish and set the spreading surface to a controlled state.²³ After etching, the surface roughness was $S_a \approx 0.4\mu\text{m}$. The S_{dq} value, which represents the root mean square of surface slope, was measured to be on the order of $1\text{-}5\mu\text{m}/\text{mm}$. In each case, the processed substrates are weighed using an analytical balance (Metler Toledo ME54E).

Spherical powders in the 45-106 μm and 15-45 μm PSD were used for these demonstrative measurements, with SEM images in Fig. 3a and 3b and bulk properties listed in Table. I.

III. METHODS

Generating and measuring the thin powder beds is based on four independent steps:

1. Powder deposition with shear press fixture
2. Contact sintering of powder in vacuum
3. Areal topography using coherence scanning interferometry

PSD	Composition	D_{10} [μm]	D_{50} [μm]	D_{90} [μm]	ϕ_{apparent}	Hall Flow Rate [s/50g]
45-106 μm	Ti-6Al-4V	47 ± 1	68 ± 1	104 ± 2	0.56	27
15-45 μm	Ti-6Al-4V	20 ± 1	28 ± 1	43 ± 1	0.57	30

TABLE I: Titanium alloy powder properties. Particle size distribution is measured using according to ASTM B822, using $N=5$ measurements

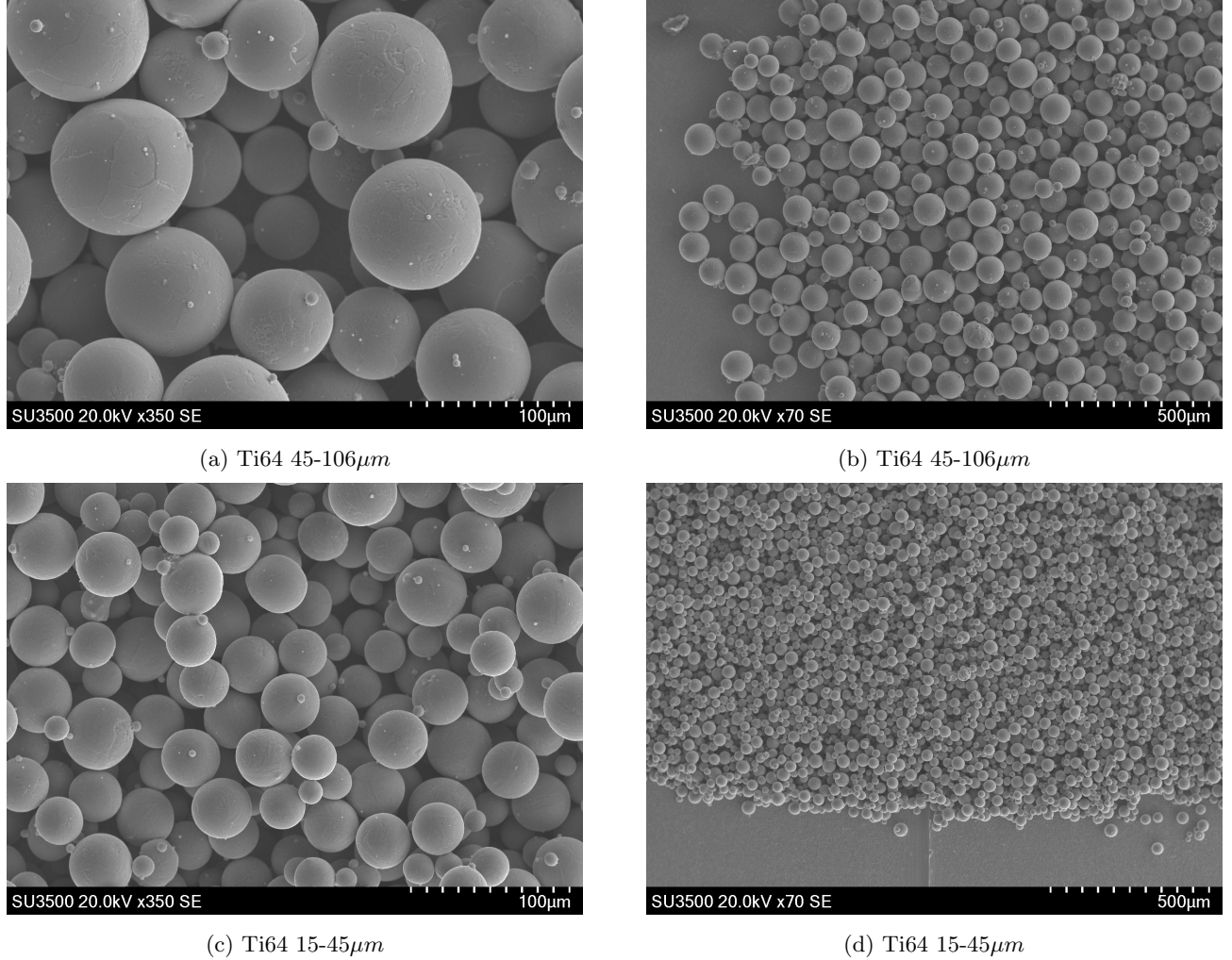


FIG. 2: Morphology and edge packing of contact-sintered Ti64 powders

4. Data post-processing to remove substrate form and generate statistics

Each processing step is relatively independent of the other, enabling this method to be adapted to different deposition and sintering methods.

1. Shear-Press Powder Deposition

Inspired by the Schulze ring-shear tester, the shear-press deposition technique is a low-cost method for

depositing single layers of powder on a consumable substrate.^{24,25}

First, the substrate is installed in a vacuum chamber and a polished aluminum funnel block is positioned on the substrate, as shown in Fig. 3a. A small mass of powder ($m_{\text{pow}} = 50\text{-}200\text{mg}$) is weighed and gently poured into the funnel, which has a polished $1/8''$ center bore. This step initiates the powder in a repeatable initial, low-stress state.

After carefully removing the funnel, the area surround-

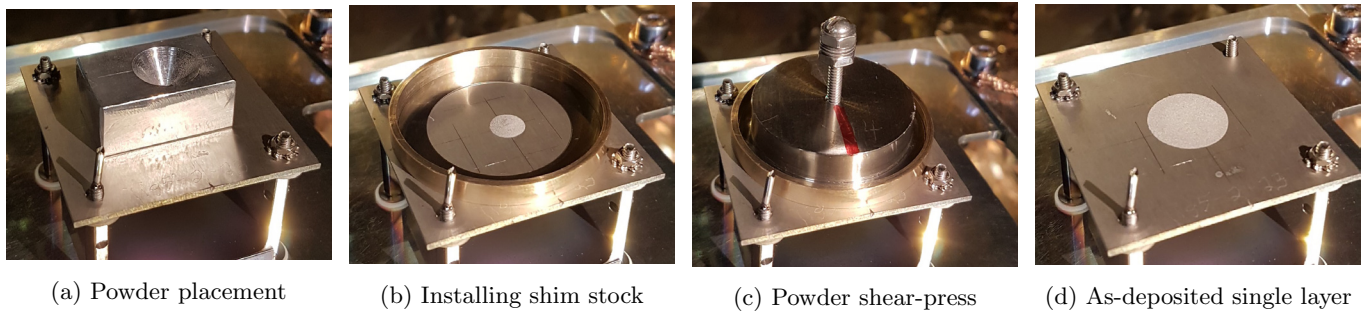


FIG. 3: Shear-press powder deposition process

ing the powder mound is gently brushed to remove any stray particles. A circular shim stock (McMaster-Carr: 98126A039) and bronze retaining ring are placed around the powder mound, as shown in Fig. 3b.

A surface-ground, stainless steel circular puck weighing 97g is then placed in the bronze retaining ring, compressing the powder between the substrate and puck, Fig. 3c. The puck is manually rotated twice at a rate of about 2 RPM, providing a combination of compressive and shear forces to the powder. By restraining the bronze ring, it has been found that operator-dependent compressive loads can be reduced.

Finally, the press, shim stock and retaining ring are removed from the substrate, and any stray particles outside the main powder disk are brushed away. SEM images of the 45-106 and 15-45 μm powder at the bed/substrate interface are shown in Fig. 3c and 3d, respectively.

This procedure includes 30 second delays between each step to minimize the possibility of powder tribo-charging. Anti-static gloves and electrostatic controls are also implemented. During deposition, the process is closely monitored using surgical loupes.

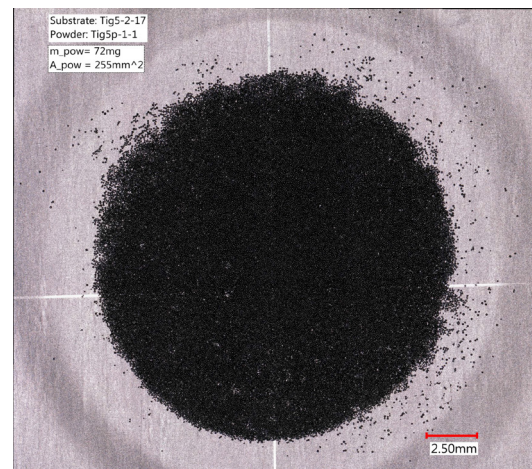
After contact sintering, the substrate and adhered powder is weighed, with the resulting powder beds shown in Fig. 4.

2. Contact Sintering

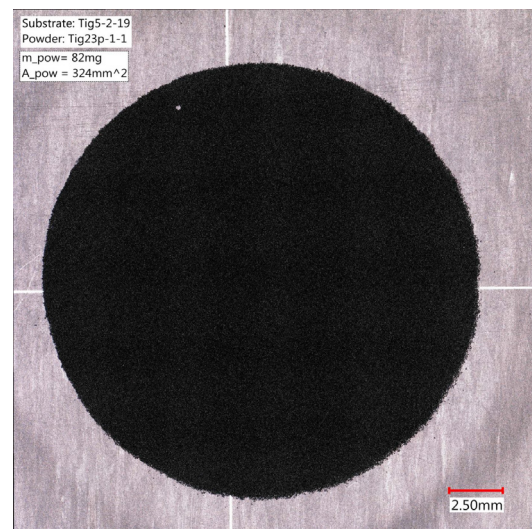
After powder has been deposited, a thin Mo foil is suspended above the bed and the chamber is slowly pumped through the viscous flow regime to a base pressure of $P < 2E - 5\text{mbar}$.

To adhere the loose powder to the substrate, a defocused electron beam is scanned over the Mo foil, radiatively heating the assembly, as shown in Fig. 5.

The empirical heating schedule raises the temperature



(a) Ti64: 45-106 μm



(b) Ti64 15-45 μm

FIG. 4: Powder bed generated using shear press, imaged at 50x and stitched using Keyence VHX-5000 microscope with off-axis lighting

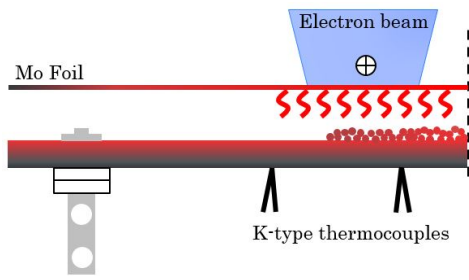


FIG. 5: Schematic of radiative contact sintering fixturing

to initiate contact sintering, a term which refers to powder which is loosely adhered to the substrate, forming electrical contact, but can be broken apart using a pliant brush. This term is synonymous with powder which is ‘melt-safe’ during EB-PBF and has kinetics related to initial stage sintering.²⁵ A key feature of contact sintering is that the powder does not undergo any significant necking, as demonstrated by the post-sintered micrographs of Fig. 3a and 3b.

3. Areal Topography

Non-contact areal topography of the beds is performed using the Zygo NewView 8000, which is based on the concept of white-light interferometry.²⁶ Briefly, a beam splitter divides the incident light between the surface under test and a Mirau interferometer. The reflected beams are recombined and captured on a charged-coupled device, where the interference fringes are correlated with the height-dependent path length differences.²⁷

To image the contact-sintered powder, the 10x Mirau objective lens with 0.5x zoom is used, which has a working distance of 7.4mm and a NA= 0.30. The lateral field of view is 1.68 x 1.68mm, with a lateral resolution of 0.95 μm and a spatial sampling distance of 1.64 μm .²⁶ Zygo proprietary software *Mx* was used to stitch multiple images.

To measure the contact-sintered powder bed, the instrument was configured to measurement type ‘surface’ and measurement mode ‘CSI-rough’, corresponding to the 40 nm bandpass F2 filter. However, the source spectrum for NewView 8000 is operated by shifting the interferometers filter between 40 nm bandpass and neutral density filters.²⁸ The system settings were specified for ‘high’ z-resolution and a vertical scan depth of 400 μm .

The focus, tilt and illumination settings were automatically generated on the solid substrate prior to powder bed characterization. The acquisition time was 53 seconds per frame, while stitched images utilized a 20% frame overlap. As detailed elsewhere, missing data due to the high incidence angle at the periphery of the metal powder has not been filled, and was omitted from analysis.²⁸

Generally, scans are performed across the diameter of the powder bed with single frame widths, generating 200-300MB data files.

4. Form remove

During contact sintering, the substrates thermally deformed, complicating the powder height measurements. To ensure the underlying form did not impact the measurements, additional MATLAB post-processing was required.

To subtract out the underlying form, shallow scribe marks were used to reference the end points of a specific areal measurements. From these datums, the height profile of the powder is measured, the powder is swept off and the profile of the bare substrate is measured.

The height profiles are then aligned, as shown in Fig. 6a. Using a polynomial fit, the form of the bare substrate is subtracted from the bed measurement, giving the local height profile of the powder, shown in Fig. 6b. This figure also includes a 300 μm wide moving average, which demonstrates the powder height fluctuations over the length scale of the electron beam full width half maximum.

IV. RESULTS

To reduce the large data sets associated with the bed measurements, the probability distribution function(PDF) of the 45-106 μm and 15-45 μm powder beds is shown in Fig. 7.

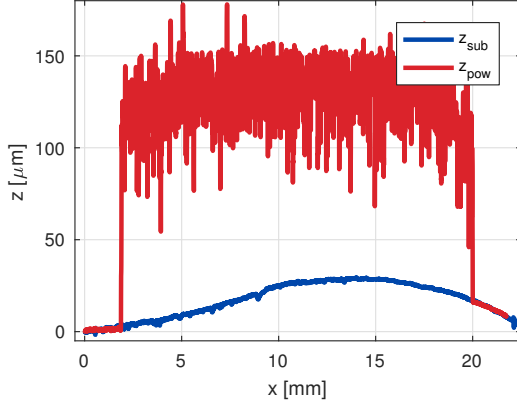
Each PDF represents the summation of 8 post-processed height profiles, composed of 4 scans along the x axis and 4 scans along the y axis. Additional statistics for each bed are given in Table. II.

V. ANALYSIS & DISCUSSION

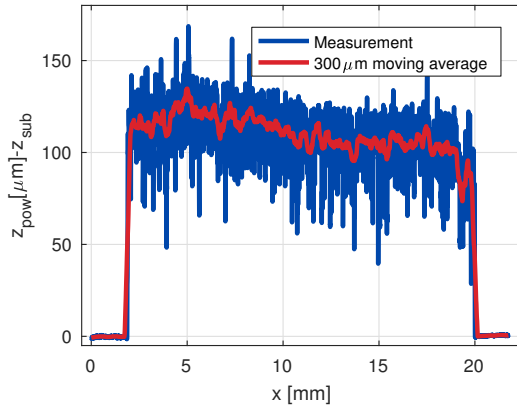
To calculate the equivalent solid height, z_{solid} , we utilize the powder mass and projected powder area mea-

PSD	mean(z) [μm]	max(z) [μm]	σ [μm]	Skewness [A.U.]
45-106 μm	104	218	± 40	-1.1
15-45 μm	109	209	± 20	-1.7

TABLE II: Results of powder bed height statistics



(a) Topographic measurements of powder/substrate and bare substrate



(b) Height profile of powder, with form of underlying substrate removed

FIG. 6: Method to remove the underlying substrate form and determine the true powder layer height

measurements shown in Fig. 4. In the case of the 45-106 μm powder of Fig. 4a, $z_{\text{solid}} = m_{\text{pow}}/(A_{\text{pow}}\rho_{\text{solid}}) = 63 \mu\text{m}$, whereas the 15-45 μm powder bed of Fig. 4b results in $z_{\text{solid}} = 57 \mu\text{m}$.

Because of the ambiguity of defining z_{bed} , calculating the packing fraction is more challenging. If $z_{\text{bed}} = \text{max}(z)$, the packing fraction according to Eq. 3 is $\phi = 29\%$ and 27% for the coarse and fine powders, respectively. Alternatively, if we assume $z_{\text{bed}} = \text{mean}(z)$, the packing fractions are $\phi = 60\%$ and 52% , values roughly equal to the apparent density.

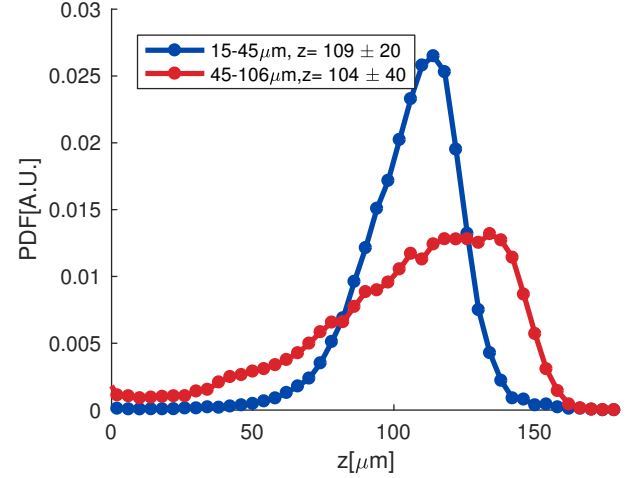


FIG. 7: Probability distribution function of powder bed height for 15-45 μm and 45-106 μm Ti64 powders

Despite having comparable results, the PDF of each powder shows a distinct shape, features which better captured by the standard deviation and skewness. It appears that the finer powder achieves complete substrate coverage, whereas the leftmost tail of the coarse powder PSD suggests some voids.

With respect to the introductory discussion of wall effects, it is illustrative to normalize the bed measurements against the median particle sizes given in Table I, with the resultant PDF is shown in Fig. 8.

In this case, we see that the bed formed from coarse powder is approximately 2.5 particles thick, whereas fine powder bed is approximately 8 particles thick. Moreover, the standard deviation of these normalized PDFs are 0.58 and 0.71 for the coarse and fine powders, values which are intuitively related to the diameter of the powder itself.

This form suggests that the scale of the layer height relative to the powder diameter affects the shape of the PDF. While these results are still preliminary, additional measurements utilizing different deposition methods and layer heights will be detailed in a forthcoming article.

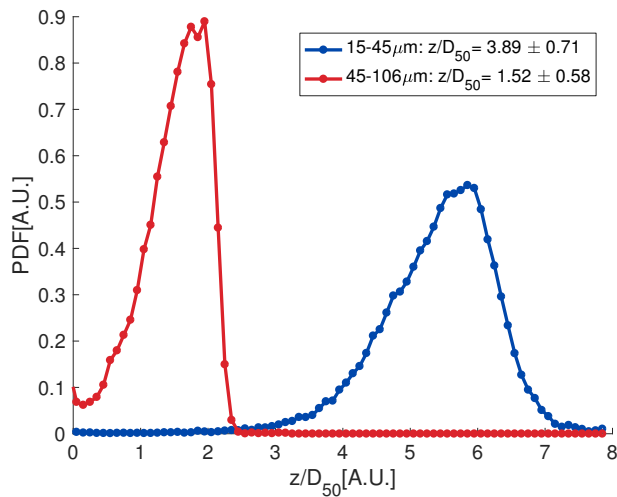


FIG. 8: Probability distribution function of powder beds height normalized against median particle diameter.

VI. SUMMARY AND CONCLUSION

A novel, low-cost method to deposit and measure single layers of powder was presented. This method is based on simple tooling, in-vacua contact sintering, high-resolution areal topography and post-measurement signal processing. A key feature of this method is based on contact sintering the powder to a removable substrate, enabling ex-situ powder weighing and optical inspection.

Measuring the areal topography of two separate particle size distributions has demonstrated that the bed probability distribution function has similar maximum and mean heights, but different PDF shapes. These differences are attributable to the scale of the layer relative to the particle size, features which we refer to as ‘wall effects’.

While these measurements are still in their preliminary stages, this approach could be adapted to study the influence of different powders and deposition methods. Additionally, by machining known features into the substrate and removing the underlying form after sintering, the relationship between the bed and the substrate roughness can also be investigated. These measurements could prove useful for developing a deeper understanding of powder and process-specific spreadability.

VII. ACKNOWLEDGMENTS

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- ¹A. T. Sutton, C. S. Kriewall, M. C. Leu, and J. W. Newkirk, “Powder characterisation techniques and effects of powder characteristics on part properties in powder-bed fusion processes,” *Virtual and Physical Prototyping* **12**, 3–29 (2017).
- ²J. H. Tan, W. L. E. Wong, and K. W. Dalgarno, “An overview of powder granulometry on feedstock and part performance in the selective laser melting process,” *Additive Manufacturing* (2017).
- ³J. A. Slotwinski and E. J. Garboczi, “Metrology needs for metal additive manufacturing powders,” *Jom* **67**, 538–543 (2015).
- ⁴A. Makes, *Standardization Roadmap for Additive Manufacturing, version 1.0* (American National Standards institute).
- ⁵M. Van den Eynde, L. Verbelen, and P. Van Puyvelde, “Assessing polymer powder flow for the application of laser sintering,” *Powder Technology* **286**, 151–155 (2015).
- ⁶A. B. Spierings, M. Voegtlin, T. Bauer, and K. Wegener, “Powder flowability characterisation methodology for powder-bed-based metal additive manufacturing,” *Progress in Additive Manufacturing* **1**, 9–20 (2016).
- ⁷R. Freeman, “Measuring the flow properties of consolidated, conditioned and aerated powders—a comparative study using a powder rheometer and a rotational shear cell,” *Powder Technology* **174**, 25–33 (2007).
- ⁸ASTM F42, “Wk55610 new standard the characterization of powder flow properties for additive manufacturing applications,”.
- ⁹C. Meier, R. Weissbach, J. Weinberg, W. A. Wall, and A. J. Hart, “Critical influences of particle size and adhesion on the powder layer uniformity in metal additive manufacturing,” *arXiv preprint arXiv:1804.06822* (2018).
- ¹⁰P. Bidare, R. Maier, R. Beck, J. Shephard, and A. Moore, “An open-architecture metal powder bed fusion system for in-situ process measurements,” *Additive Manufacturing* **16**, 177–185 (2017).
- ¹¹Y. Sun, S. Gulizia, C. Oh, C. Doblin, Y. Yang, and M. Qian, “Manipulation and characterization of a novel titanium powder precursor for additive manufacturing applications,” *Jom* **67**, 564–572 (2015).
- ¹²S. Grantham, B. Lane, J. Neira, S. Mekhontsev, M. Vlasea, and L. Hanssen, “Optical design and initial results from nist’s ammt/temps facility,” in *Laser 3D Manufacturing III*, Vol. 9738 (International Society for Optics and Photonics, 2016) p. 97380S.
- ¹³J. Whiting and J. Fox, “Characterization of feedstock in the powder bed fusion process: Sources of variation in particle size distribution and the factors that influence them,” in *Solid Freeform Fabrication Symposium Proceedings, Austin, Texas, USA* (2016).
- ¹⁴P. J. DePond, G. Guss, S. Ly, N. P. Calta, D. Deane, S. Khairallah, and M. J. Matthews, “In situ measurements of layer roughness during laser powder bed fusion additive manufacturing using low coherence scanning interferometry,” *Materials & Design* (2018).
- ¹⁵M. Larsson and A. Snis, “Method and device for producing three-dimensional objects,” (2012), US Patent 8,187,521.

- ¹⁶C. Eschey, S. Lutzmann, and M. Zaeh, "Examination of the powder spreading effect in electron beam melting (ebm)," Solid Freeform Fabrication, Austin, TX, August , 3–5 (2009).
- ¹⁷C. Körner, "Additive manufacturing of metallic components by selective electron beam melting: a review," International Materials Reviews **61**, 361–377 (2016).
- ¹⁸C. Boley, S. Khairallah, and A. Rubenchik, "Calculation of laser absorption by metal powders in additive manufacturing," Applied optics **54**, 2477–2482 (2015).
- ¹⁹P. Fischer, V. Romano, H.-P. Weber, N. Karapatis, E. Boillat, and R. Glardon, "Sintering of commercially pure titanium powder with a nd: Yag laser source," Acta Materialia **51**, 1651–1662 (2003).
- ²⁰A. B. Spierings and G. Levy, "Comparison of density of stainless steel 316L parts produced with selective laser melting using different powder grades," in *Proceedings of the Annual International Solid Freeform Fabrication Symposium* (Austin, TX, 2009) pp. 342–353.
- ²¹F. A. Dullien, *Porous media: fluid transport and pore structure* (Academic press, 2012).
- ²²H. Mindt, M. Megahed, N. Lavery, M. Holmes, and S. Brown, "Powder bed layer characteristics: the overseen first-order process input," Metallurgical and Materials Transactions A **47**, 3811–3822 (2016).
- ²³Y. Mizuno, A. Tanaka, K. Takahiro, T. Takano, Y. Yamauchi, T. Okada, S. Yamaguchi, and T. Homma, "Hydrogen outgassing from titanium-modified layers with various surface treatments," Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films **19**, 2571–2577 (2001).
- ²⁴D. Schulze, "A new ring shear tester for flowability and time consolidation measurements," in *Proc. 1st International Particle Technology Forum* (1994) pp. 11–16.
- ²⁵P. Carriere, *Energy and Charge Transfer during Electron Beam Melting*, Ph.D. thesis, McGill University (2018).
- ²⁶P. de Groot, "Principles of interference microscopy for the measurement of surface topography," Advances in Optics and Photonics **7**, 1–65 (2015).
- ²⁷N. Senin, A. Thompson, and R. K. Leach, "Feature-based characterisation of signature topography in laser powder bed fusion of metals," Measurement Science and Technology (2017).
- ²⁸C. Gomez, R. Su, A. Thompson, J. DiSciaccia, S. Lawes, and R. K. Leach, "Optimization of surface measurement for metal additive manufacturing using coherence scanning interferometry," Optical Engineering **56**, 111714 (2017).

Challenges and quality implications of feedstock cross-contamination of metal powders: an industrial perspective

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INTRODUCTION

Amongst the challenges of bringing Additive Manufacturing (AM) from lab to market is not only the technical issues of production capabilities, scalability and identification of proper applications. High standards are needed in the tool-shop environments in order to ensure consistent production of multiple parts across machines, operators, and manufacturing facilities. AM dedicated laboratories and production sites are becoming more common and at the same time, new questions arise in regard to requirements and how to meet these high standards, e.g. achieving constant characteristics of the powders in connection to the machine parameters and work environment [1]. In this context, this paper focuses on the challenges faced when establishing such AM facilities, e.g. for production or research, and it aims to specifically address the potential side-effects related to cross-contamination of powder feedstock and its effect on precision and quality of the final parts.

Metal powder particles used in powder-based AM processes are in the range of 20-100 μm in size and are easily subjected to migration when entering an air flow. During powder handling, e.g. build chamber cleaning operations, refill of reservoir with virgin powder, etc, the particles can enter linger in the surrounding environment for prolonged amounts of time. This will increase the risk of a powder particles to stick to the clothes of machine operators who then carry

them in the surrounding environment, possibly contaminating subsequent production. This has been acknowledged mainly with direct experience. In some cases, the microstructure analysis of a component showed the presence of foreign material who could not really been explained. In fact, the inclusion's material has not been in use in the facility since more than six months suggesting that it might not be a unique case.

Defects within metal components made with powder bed fusion processes are widely studied, e.g. porosities, micro-cracking and poor particle bonding. Their negative effect on part properties, e.g. tensile strength and fatigue, is widely acknowledged and reported largely in academic literature [2]. Despite this, little could be found in literature about categorizing in-situ cross-contamination of powders as a possible cause of defects within the part, and as a main factor affecting quality, precision and mechanical properties of AM parts. It is commonly accepted that cross-contamination of feedstock powders *may* affect the properties of the final part, for example contributing to inconsistent layer adhesion due to difference in melting temperature[3] but the extent of the problem is still dubious.

As the development of AM increases by the day, more production sites are expected to expand and adapt to a more AM inclusive environment. In this context, single-material machine set-ups are advisable for high

performance application components, e.g. aerospace [4], [5], however this may represent a challenge for research facilities with a smaller capacity but a wide portfolio of products and materials.

This paper aims to recognize and ordain appropriate measures with relation to the hidden risks of cross-contamination of the powder from which geometry is consolidated in powder-bed fusion systems and to present a possible framework for the prevention of in-situ cross-contamination of feedstock.

AM PROCESS LIFE CYCLE AND KEY INFLUENCING FACTORS TO PART QUALITY; AN OVERVIEW

Quality control is a widely used resources within manufacturing processes. Mapping the whole manufacturing process is a necessity to gain in depth knowledge of influencing factors within the process and to being able to reach high standards of production. In literature a number of studies in this area that have attempted to create a comprehensive overview of the AM process and Figure 1 shows in broad terms, what are the key aspects that have an impact on the final part.

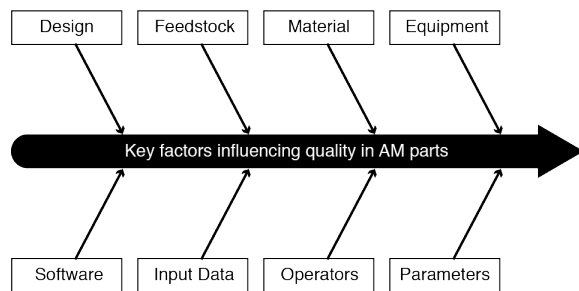


Figure 1 Main influencing factors on the quality of the final AM part

In Figure 1 the main factors influencing the quality of AM parts are listed as: design, feedstock, material, equipment, software, input data, operators and process parameters. All of these have equal importance in the process, however in this paper, only the aspects related to the feedstock and the materials will be covered. A reliable certified material supplier, in-process monitoring and testing after the build

are fundamental when aiming for part quality, reliability and to achieve high process repeatability. Especially so, with the rise of AM as a direct manufacturing technology and with increasing demands for compliance. A growing number of powder manufacturers are now specializing in the production of AM powders and they are becoming more aware of the necessary preventive measures in order to avoid accidental cross-contamination of non-compatible feedstock and defects. In fact, the quality of the incoming materials in the machine are critically important to the outcome of the part. On top of that, the material behavior is followed along during production, with in-process monitoring procedures, and afterwards by means of destructive or non-destructive testing, where the part is cut up and inspected for inclusions and defects.

CHALLENGES RELATED TO METAL POWDER HANDLING

In an ideal scenario of AM production, there would be one powder metal machine used for a single metal powder material, in order to minimize the occurrence of in-situ cross-contamination during production. In many cases, it is not uncommon to find multiple powder metal machines operating a single material each on the same production floor. Challenges however start to occur when materials of different nature are used, especially metals with different characteristics, e.g. reactive and non-reactive. In this context the authors believe that there is a poor understanding of the behavior of the powders in the air and of how this could affect the quality of the components. During the handling of the metal powders, due to the small size of the particles, the material may enter the air flow and circulate in the surrounding area. Additionally, when operating the machine, technicians become exposed to powders increasing the likelihood of carrying the different powders with them from one machine to the others. Although appropriate, and strict, procedures can help in these scenarios, the risk of contamination still

exists and, because of the unpredictability of the particles behaviors in the air, the effects of it cannot be controlled properly. For this reason, the authors believe it is necessary to map the intermediate steps of the powder handling within the production process, highlight the points where risks of contamination are higher and come up with solutions to minimize the contamination during these operations.

Mapping the critical steps during the process of metal powder handling

From the moment the material arrives to the production facility to the moment when the AM part is manufactured; the operator has to carry out a series of steps that require different degrees of exposure to metal powders. The most critical steps are during the machine preparation time, e.g. removing the build plate, cleaning the build envelope and replacing the build plate. During these steps the operator has a direct contact with the interior of the machine. A summary of these steps is shown in Table 1, which highlights the most critical steps.

Table 1 Steps required for machine preparation. Highlighted are the critical steps where the operator is directly in contact with the powder and where the powders are at risk of entering the air flow.

	Operation	Direct exposure to powders
1	Machine cool down	No
2	Remove excess powder around the part	No
3	Open machine	Yes
4	Remove build plate from machine	Yes
5	Transport build plate to right location	Yes
6	Clean machine from excess powder	Yes
7	Insert new build plate	Yes
8	Calibrate the machine	Yes
9	Close machine	No
10	Refill machine with virgin powder	No

A PRAGMATIC APPROACH FOR THE AVOIDANCE OF CROSS-CONTAMINATION IN PRODUCTION R&D FACILITY

AMEXCI is a Swedish startup, privately owned by 11 different companies, 10 of which are big players in the global manufacturing industry [6]. Recently AMEXCI has built a new workshop facility that will be used for R&D purposes in the field of AM. The current capacity for powder systems is: one EOS P396 (polymer), two EOS M290 (one for reactive and one for non-



Figure 2 Schematic of the workshop floor. (1) Changing rooms, (2) Preparation room, (3) Air lock, (4) Machine rooms, (5) powder rooms, (6) Post processing.

reactive metals), one Aconity MIDI. Due to the variety of industries served by the



Figure 3 Workshop with the machines located in separated rooms with glass walls. Each room has a roll-up door.

company, the type of materials will vary over time. It is therefore paramount for the company to have an impeccable plan. In this regard AMEXCI, having had the possibility of building the workshop from scratch, has adopted various measures in order to minimize, if not avoid, the cross-

contamination of the metal powders. The measures taken involve both the construction of the workshop and the handling procedures. These can be summarized as following:

- Each AM machine is in a room separate from the others (Figure 2 and Figure 3 **Error! Reference source not found.**)
- Each powder material has its own preparation and handling room (Figure 2)
- Each room has an appropriate ventilation system. This pushes the powders top-down and sucks them from the lower level to the back of the room
- Each room has a roll-up door to prevent agitation of air and to reduce the stirring of powders particles (Figure 3)
- Operators have to go through an air lock when entering the workshop and every time before entering another room with machines or powders
- A monitor system has been installed to keep track of the powder activity in the different areas of the workshop over time and determine the behavior of the powders

CONCLUSIONS

The paper discussed the issues related to cross-contamination of metal powder in production R&D facilities and proposed an approach to limiting the occurrence of this phenomenon by separating each machine in a different room and by establishing a strict internal procedure for handling. Although the effect of cross-contamination of powders is not widely discussed or addressed in literature, we believe it plays a very important role in the industry as it may have significant effects on critical components leading to cracks and ultimate failures.

FUTURE WORK

Track cross-contaminants throughout the facility would be the next step in order to better understand the challenge of cross-contamination and particle behavior within an AM production facility. Although challenging to track the amount

of contaminant that will be transferred, methods similar to those used within the food-production industry could be used. This approach would be useful to track the cross-contamination introduced by the operator.

REFERENCES

- [1] B. J. Dawes and R. Bowerman, "Introduction to the Additive Manufacturing Powder Metallurgy Supply Chain Exploring the production and supply of metal powders for AM processes," *Johnson Matthey Technol. Rev.*, no. 3, pp. 243–256, 2015.
- [2] B. Zhang, Y. Li, and Q. Bai, "Defect Formation Mechanisms in Selective Laser Melting: A Review," *Chinese J. Mech. Eng.*, vol. 30, no. 3, pp. 515–527, 2017.
- [3] S. Fulga, A. Davidescu, and I. Effenberger, "Identification of in-line defects and failures during Additive Manufacturing Powder Bed Fusion processes," *MATEC Web Conf.*, vol. 94, 2017.
- [4] A. D. Brandão *et al.*, "Challenges in Additive Manufacturing of space parts: Powder feedstock cross-contamination and its impact on end products," *Materials (Basel)*, vol. 10, no. 5, 2017.
- [5] M. Seifi, A. Salem, J. Beuth, O. Harrysson, and J. J. Lewandowski, "Overview of Materials Qualification Needs for Metal Additive Manufacturing," *Jom*, vol. 68, no. 3, pp. 747–764, 2016.
- [6] AMEXCI AB, "www.amexci.com."

Optimization of surface determination strategies to enhance detection of unfused powder in metal additive manufactured components

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Abstract

The evolution of industrial computer tomography in recent years has enabled the inspection of the integrity of mechanical components without sectioning or destroying them. For many valuable components and prototypes nondestructive inspection (NDI) can save precious time and costs allowing for pre-failure detection and accurate finite element analysis.

The mechanical properties of cast components are well documented and nondestructive inspection is well established, but with additive manufacturing (AM) quickly being recognized as a core technology for producing complex and individual components the need for well understood NDI is more urgent than ever.

The challenges in inspecting (AM) components are quite different than cast ones and unfused powder detection is one of the biggest issue, as the powder size used in sintering the (AM) component can be smaller than 20 μm .

Detecting small pores/defects of such a size requires the use of high magnification and bespoke XCT settings.

This paper investigates the impact of surface determination on the detection of unfused powder in a EBM process and assesses the ability of utilizing the standard ISO 50 surface determination protocol to visualize this.

The powder used was Ti6AL4V 45-100-micron grain, chosen as it is the powder commonly used in an Arcam electron beam melting (EBM) machine. A Nikon XTH 225 (Nikon Metrology, Tring) industrial CT was used to analyze the pores/ defects' location and volume.

Defects of between 50 and 1400 microns in diameter were machined into the surface of the designed artefact using a CNC machine equipped with micro-drills. Once this was achieved, the defects were characterized using a Alicona G4 (Alicona, Graz) focus variation instrument. Virgin Ti6AL4V powder was then

added to fill the 1400 μm and 500 μm diameter defects.

Data processing, surface determination process and defect analysis was carried out using VG Studio Max 3.1 (Volume Graphics, Heidelberg). The focus of the study is on providing best practice guidance regarding the selection of inspection parameters and identifying the capability of ISO 50 surface determination in detecting unfused powder.

Introduction

The pores found in additive manufactured components are different from those found in cast alternatives. In the additive manufactured components, the pores could be hollow, filled with partially fused powder or unfused powder. The pores found in cast components are usually hollow.

The unfused powder can be as small as 45 μm (AP&C, 2017) when considering EBM manufactured components and respectively 15 μm for selective laser melting (SLM) (Sim-solutions.com, 2017).

X-ray computer tomography (CT) is a NDI method that has the capability to detect porosity whilst analyzing the component volume providing position, location distribution and volume of any pores/defects. Usually the data obtained from the scan consists of a volumetric file that contains specific gray values for each three-dimensional pixel (voxel). Data analysis is usually done by proprietary software (e.g. Volume Graphics VG Studio Max, Avizo) to threshold and segregate between gray values of the background and object material.

The results are presented in the form of histogram which is plotting the number of voxels versus gray value. In the case of single materials the histogram will contain two peaks: one peak will represent the air and the other will represent the material. A single threshold (ISO) grey value in the grayscale between the two peaks represents the edge of the material. The automated algorithm commonly used and cited in

the engineering applications is ISO 50% surface determination. (Yagüe-Fabra et al., 2013) (Borges de Oliveira et al., 2016) ISO 50% shown in figure 1 automatically positions the threshold within equal distance between the maximum values of the two peaks of the histogram.

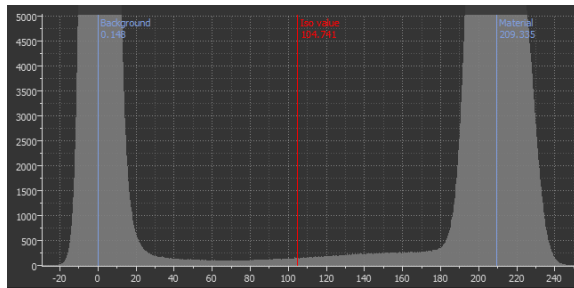


Figure 1 Histogram image for single material.

There is no specific scientific explanation for selecting ISO 50%, furthermore implementing an inappropriate ISO value could erroneously classify some material as air and vice versa. This will result in a failure to detect the edge of the component (Kowaluk and Wozniak, 2017). An earlier study carried out at K.U. Leuven showed that ISO 50% will result in dimensional shrinkage for aluminum and elongation for steel and ZrO₂. The study recommended utilizing ISO values 35-45% and 80-90% for aluminum and steel respectively (Kruth et al., 2011).

This study investigates the ability of ISO 50% in detecting unfused powder in EBM built artefact and exploring the ability of improving the results by selecting different ISO value thresholds. Defects containing unfused powder of great concern for additive manufactured parts as the gray value of the unfused or semi fused powder particles is very close to the material ones. Therefore an accurate threshold (ISO) value selection is mandatory. An artefact was designed for this study based on representative actual pores identified in an earlier industrial project covered with NDA.

Methodology

In this experiment a Nikon XTH225 industrial XCT was used to characterize a Ti6AL4V artefact built using an Arcam Q10 electron beam-melting machine (EBM). Prior to scanning 50 μ m (defect 4), 100 μ m (defect 3), 500 μ m (defect 2) and 1400 μ m (defect 1) holes were drilled into the

polished surface of the artefact using a CNC machine equipped with micro drills and end mills as shown in figure 2a, the holes are designated to be representative of typical defects. The 50 and 100 μ m diameter holes were left as voids whilst the 1.4mm and 0.5mm figure 2b diameter holes were selected to be filled with powder.

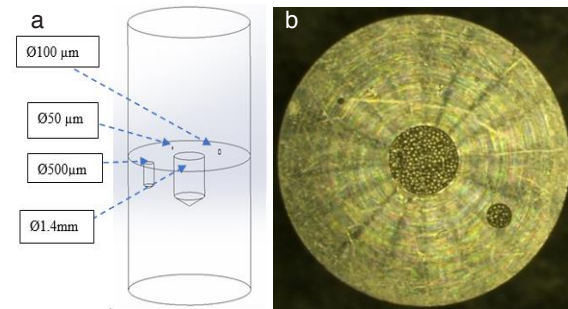


Figure 2 a) Artefact 3D model, b) top view of the artefact with defect 1 and filled with powder.

In this study the component was built using EBM AM machine the powder deposition layer thickness is approximately 40 μ m (Dsiac.org, 2017), therefore the 50 μ m defect will simulate single layer disruption. The 100 μ m will replicate a two-layer disruption. The artefact consists of 2 halves, the lower half contains the drilled defects. The surface of both halves was machined using a diamond cut finish, whilst the mating upper half with the same diameter is designed to enclose the drilled holes thus creating internal defects/pores. The principle of ringing two surfaces together is similar to that employed for slip gauges. (Tawfik et al., 2018).

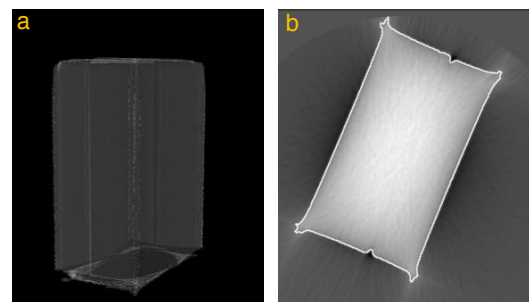


Figure 3 a) 3D image of the scanned 2 gauge blocks b) Top view of 2 gauge blocks

Figure 3a shows a 3D image of the slip gauges and 3b shows a top view of two slip gauges rung together. From the images it was concluded that the gap between the two slip gauges is too small to be detected by the XCT machine.

The drilled defects were characterized using a focus variation microscope (Alicona G4). The measurements aimed to characterize each defect and to determine the reference values for the diameter, depth and calculated volume prior to ringing the two halves together. Prior to measurement the Alicona was calibrated as per the manufacturer's recommendations.

The drilled defects/pores depth and diameter were measured using AliconaG4 focus variation microscope, then each defect volume was calculated by assuming that each drilled hole consists of combined cylinder and cone. The defects diameters were measured by using three point best fit circle (figure 4b). The depth was measured by selecting two points on the upper surface and creating a horizontal line and a point on the lowest point in the drilled hole (figure 4a).

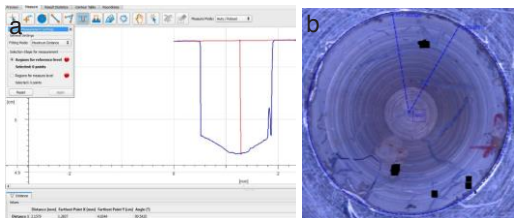


Figure 4a) Alicona value for defect 1 depth b) Alicona value for defect 1 radius

The artefact was then scanned with Nikon XTH 225 to create a volume file of the entire artefact. The XCT scanning parameters were optimized to ensure that measurement noise is minimized as shown in table 1.

Table 1. Settings used for CT measurements

Filter	0.5mm Cu
Exposure	4000 ms
Filament current	8.6 W
Acceleration voltage	150 KV
Voxel size	8 μm
Gain	12

The data obtained was analyzed using Volume Graphics VGStudio Max 3.0 to accurately quantify the unfused powder volume and determine the gray value threshold. The diameter and depth of each defect was evaluated three times by using geometry measurements tools in the software.

To determine the adequate ISO threshold three different methods were employed: manually selecting background and material, selecting

automatic ISO 50; and manually identifying grey values of the pores/defects.

In a second experiment defect 1 and 2 were filled with unfused powder identical to the one used to manufacture the artefact (Ti6AL4V). After filling the defects, the artefact was measured using the same settings and procedures as presented in table 1. The obtained scans were analyzed using two different surface determination strategies: ISO 50% and manually identifying grey values of the pores/defects to compare the defects' volumes.

Results

The two surface determination strategies, namely; manually selecting background and material, and selecting automatic ISO 50% failed to detect the unfused powder. Furthermore, the ISO value for both strategies was identical.

The gray value of the unfused powder was subsequently manually identified and then the obtained value was selected as the threshold surface gray value.

Optimizing this threshold value enabled the detection of the overall contour of the pore and the gaps between the unfused powder particles. Figure 5 shows the difference in detected powder particles between the ISO 50% method (figure 5a) and optimized threshold value (figure 5b).

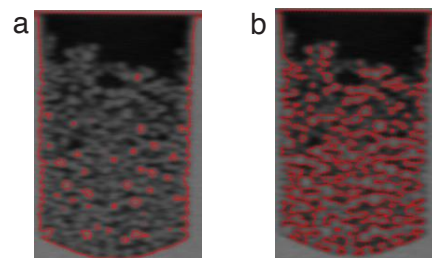


Figure 5 a) Defect 1 with ISO 50%, b) defect 1 with optimized ISO value

The results of the defects diameters are presented in table 2, the custom ISO values are closer to the Alicona values than the ISO50% results

Table 2 Defects diameter results (μm)

	Defect1	Defect2	Defect3	Defect4
Alicona	1434	526	142	86
XCT ISO 50%	1402	489	114	48
XCT Custom ISO	1429	521	138	82

It was also noted from values in the above table that the error is significantly higher in the ISO50% results for smaller defects.

Table 3 presents the results for defects depth and was noted from the depth results that the custom ISO values are closer to the Alicona values than the ISO50%.

Table 3 Defects depth results

	Defect1	Defect2	Defect3	Defect4
Alicona	2157	1090	280	12
XCT ISO 50%	2094	1017	244	59
XCT Custom ISO	2149	1081	291	84

Finally, after filling defect 1 and 2 with powder, the artefact was scanned and the results obtained for the volume of defect 1 and 2 using ISO50% was 0.331 and 0.0689 mm³ respectively. Whilst using custom ISO threshold the volume for defect 1 and 2 was 1.786 and 0.187 mm³.

Discussion

Utilizing the ISO 50% approach is widely cited and is the generally accepted method for XCT surface determination of single material components. This experiment proved that the gray values of pores and powder defects of additive manufactured components are such that they require a different, more bespoke approach to be adopted. This study presents a generalized approach to determine the threshold level in AM produced components by manually defining the maximum gray value of the pore.



Figure 6 Defects diameter comparison μm

Figure 6 shows a comparison between the results of defects diameter obtained with Alicona, XCT with ISO50% surface determination and XCT with optimized ISO value.

The difference in value between Alicona and ISO50% for defect 1 is 2.2% and defect 2 is 7%, for defect 3 and 4 are 20% and 56% respectively.

Comparing custom ISO to the Alicona results, the difference in defect 1 is 0.4%, 1% for defect 2, 2.8% for defect 3 and defect 4 is 4.7%.

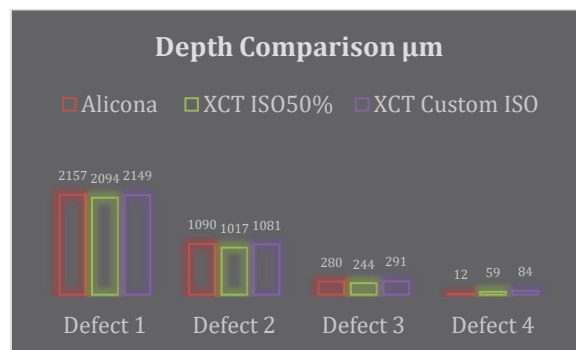


Figure 7 Defects depth comparison μm

Figure 7 shows a comparison between the results of defects depth obtained with Alicona, XCT with ISO50% surface determination and XCT with custom ISO value.

The differences between the Alicona and ISO 50% results for defect 1 and 2 are 3% and 6.7% respectively. For defect 3 the difference is 12.9% and for defect 4 70%. Comparing custom ISO to the Alicona results, the difference in defect 1 is 0.4%, defect 2 0.9%, defect 3 3.8% and defect 4 is 86%. For defect 4 the Alicona depth measurement result should be ignored due to the inability of the instrument to correctly image the bottom of the defect.

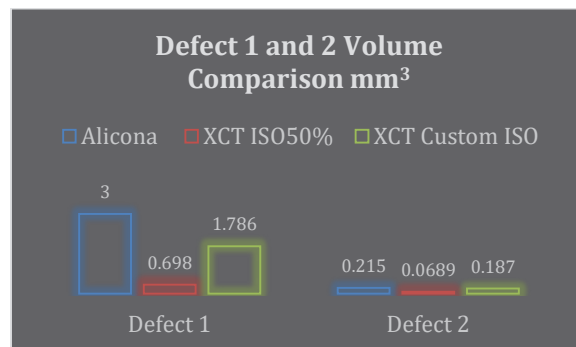


Figure 8 Defect 1 and 2 volume comparison

Figure 8 shows the difference in volume between the measurements carried out with the Alicona, XCT with ISO50% surface determination and XCT with custom ISO value for defect 1 and 2 filled with unfused powder.

The volume result obtained from the Alicona was calculated assuming the defect shape is a combination between cone and cylinder. This method for calculating volume could introduce a small error due to the radius at the lower section of the hole. The volume of defect 1 is 3mm³ when

hollow. Comparatively the XCT ISO50% volume for defect 1 filled with powder is 0.698mm³ and represents mainly the area at the top of the defect not filled with powder. When evaluating the custom ISO volume of 1.786mm³ it is apparent that the spaces between the unfused powder particles throughout the defect have also been quantified.

For defect 2 hollow is 0.215mm³, XCT ISO50% filled with powder 0.0689mm³ and for custom ISO is 0.187mm³. Similarly the custom ISO value was able to discern the spaces between powder particles.

The results of the volume comparison prove that ISO50% successfully detected the pores filled with air but failed in detecting the individual contours of the unfused powder. As shown in figure 5a it failed to detect most of the unfused powder particles and just assumed a solid material.

The custom ISO threshold detected the cavities between the powder particles, it was also noted that for this study the gray value threshold was 139, which corresponds to ISO70%.

Conclusion

The results of this study confirm that ISO50% is not the appropriate threshold for porosity analysis and for detecting unfused powder. The study has shown that to identify individual powder particles the exact gray value must be used.

The gray value of the unfused powder tends to be closer the material peak in the histogram.

Visual inspection should be used to accurately identify the required threshold for surface determination.

Optimization of surface determination can enhance the capability of non-destructive inspection to detect unfused or semi fused powder.

It was also noted that the surface threshold values required for accurate porosity detection is different than that needed for outer surface profile measuring.

The threshold for surface determination is dependent on the material, material thickness and scanning parameters. Therefore scanning the same part with two different parameters will result in different ISO values.

Further studies will be carried out to investigate ISO values for different materials and to evaluate the impact of optimized ISO value for sub-voxel porosity detection.

REFERENCES

- [1] AP&C. (2017). *Powders designed for Additive Manufacturing - AP&C.* [online] Available at: <http://advancedpowders.com/our-plasma-atomized-powders/spherical-powders-designed-for-additive-manufacturing/> [Accessed 13 04. 2018].
- [2] Slm-solutions.com. (2017). *Selective Laser Melting Machine SLM 500* [SLMSolutions. [online] Available at: <https://slm-solutions.com/products/machines/selective-laser-melting-machine-slm-500> [Accessed 13 04. 2018].
- [3] Borges de Oliveira, F., Stolfi, A., Bartscher, M., De Chiffre, L. and Neuschaefer-Rube, U. (2016). *Experimental investigation of surface determination process on multi-material components for dimensional computed tomography.* open access.
- [4] Yagüe-Fabra, J., Ontiveros, S., Jiménez, R., Chitchian, S., Tosello, G. and Carmignato, S. (2013). *A 3D edge detection technique for surface extraction in computed tomography for dimensional metrology applications.* CIRP Annals.
- [5] Kowaluk, T. and Wozniak, A. (2017). *A new threshold selection method for X-ray computed tomography for dimensional metrology.* Precision Engineering.
- [6] Kruth, J., Bartscher, M., Carmignato, S., Schmitt, R., De Chiffre, L. and Weckenmann, A. (2011). *Computed tomography for dimensional metrology.* CIRP Annals.
- [7] Dsiac.org. (2017). *Nondestructive Inspection of Additive Manufactured Parts in the Aerospace Industry | DSIAC.* [online] Available at: <https://www.dsiac.org/resources/journals/dsiac/summer-2016-volume-3-number-3/nondestructiveinspection-additive> [Accessed 19 June. 2018]
- [8] Tawfik, A., Bills, P., Blunt, L. and Racasan, R. (2018). *Development of an artefact to detect unfused powder in additive manufactured components using X-ray CT.* [online] Ndt.net. Available at: https://www.ndt.net/article/ctc2018/papers/ICT2018_paper_id119.pdf [Accessed 10 Jun. 2018].

CHARACTERIZATION OF AM METAL POWDER WITH AN INDUSTRIAL MICROFOCUS CT: POTENTIAL AND LIMITATIONS

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INTRODUCTION

Final precision of parts produced by Selective Laser Melting (SLM) and other Powder Bed Fusion (PBF) technologies relies on material inputs. Powder characteristics not only influence part density, mechanical properties and microstructure but also geometrical parameters, such as the applicable minimum layer thickness, the maximum overhang angle and the overall final surface quality [1]. Effective metrology techniques are therefore needed to characterize both particle size distribution and morphology, and to follow the evolution of these characteristics during different builds after powder sieving and reuse.

Cone-beam computed tomography (CT), as studied for instance in the field of sand and soil particles characterization [2], has shown a significant empirical potential as an all-in-one tool to characterize size and shape at grain scale. However, compared to these previous studied applications, SLM powder has much smaller particles which imposes a new challenge on CT powder characterization.

CT reconstruction generates a 3D voxelized attenuation map of the measured object from a series of 2D projections acquired at different perspectives. Image segmentation is used to delineate objects for further analysis. A number of factors affects the cone-beam CT measurement performance of micro-objects, such as spatial resolution loss due to the focal spot blurring effects and high sensitivity to inaccuracy in a magnification factor.

This work explores potential and limits of industrial microfocus CT (μ -CT) as an all-in-one tool to characterize the morphology of metallic Additive Manufacturing (AM) powder, the particles size distribution and, possibly, the contamination of the feedstock powder.

μ -CT STUDY FOR AM POWDER ANALYSIS

AM powder samples

For the study, we selected three different powder samples from a specialized AM powders

producer, with D10-D90 of the distribution as listed in the vendor's specifications:

- **Mar300 15-45:** Maraging 300 Alloy Steel powder 15-45 μm ;
- **Mar300 5-25:** Maraging 300 Alloy Steel powder 5-25 μm ;
- **Ti-CP 15-45:** Titanium CP powder 15-45 μm .

To confirm the vendor's specifications and to validate the subsequent μ -CT analysis, laser diffraction (LD) measurements were obtained by means of a Beckman Coulter's LS 13 320. The underlying mathematics of LD measurements assume spherical particles to reconstruct the diffraction pattern. This is a reasonable assumption for virgin powders, and LD analyses can be adopted as a reference for the following μ -CT study.

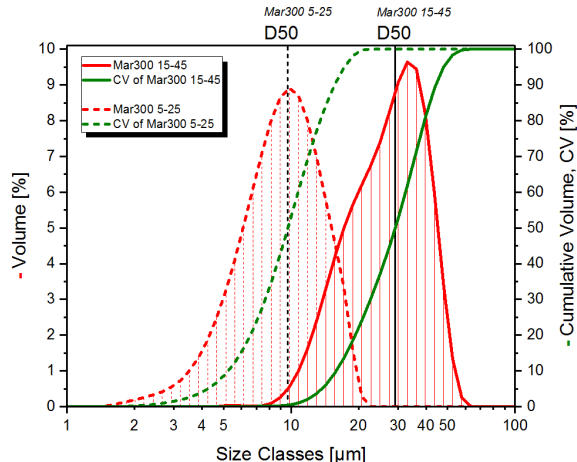


FIGURE 1. LD distribution curves of Maraging 300 powders.

Particle size distributions from LD are presented in Figure 1 for the Maraging 300 powders. The particle size distribution for the Ti-CP 15-45 sample was nearly identical to the Mar300 15-45, therefore it is not shown in the figure. Results for all three samples are summarized in Table 1, with D10, D50, D90 cumulative volume fractions and the average particle sizes.

TABLE 1. Summary of LD analyses of the three powder samples.

SAMPLE	D10 [μm]	D50 [μm]	D90 [μm]	AVG [μm]
Mar300 5-25	5.2	9.6	15.6	9.2
Mar300 15-45	15.9	29.2	44.4	27.6
Ti-CP 15-45	19.8	32.2	44.3	30.5

The average particle size for the Mar300 5-25 sample is out of specifications, presenting a D90 of 15.6 μm instead of 25 μm. This could impede further investigations of this powder with the selected μ-CT system due to its finite spatial resolution.

Experimental setup

Spatial resolution is one of the limiting factors in μ-CT data analysis and, consequently, there should be a sufficient distance between two objects to differentiate them. Separating particles from one another has been reported as the main issue in CT metrology of fine metallic powder [3], and a good dispersion of the particles in the specimen is advised. Specimens' preparation for this study is realized by dry spraying powder on a double-sided tape and subsequently rolling the tape on a 3 mm wooden stick. This approach allows to relatively uniformly distribute the powder particles and to limit sample dimensions to achieve high CT magnifications.

μ-CT scans were performed on a Nikon XTH 225ST machine at 80 kV, 80 μA, exposure 2000 ms, and tungsten target. In total, 3600 projections were acquired at a magnification of 69 and reconstructed with a voxel size of 2.9 μm. One of the usual concerns associated with high magnification scans is blurring due to finite focal spot size. The total power was therefore limited to constrain the X-ray gun focal spot size around 3 μm, which is the smallest possible for the used machine.

Voxel scaling factor

Discrepancy between nominal and actual positioning of the sample with respect to the source and the detector due to machine's kinematic errors can introduce significant errors in dimensional measurements [4]. Given the high magnification, common artifacts [5] were not suitable; therefore a new object ("fish-eggs" artifact) consisting of 1 mm high precision (Grade 10, ISO 3290-1:2014) stainless steel spheres was designed to calculate the voxel rescaling factor.

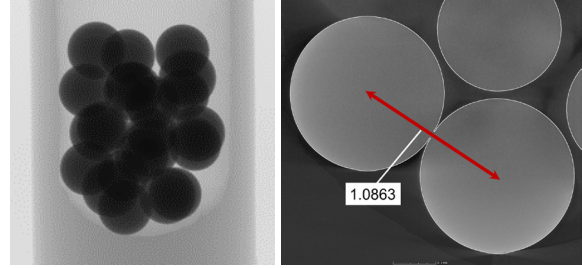


FIGURE 2. (Left) Example of μ-CT projection of the "fish-eggs" artifact; (Right) after reconstruction, touching high-precision spheres are selected for center-to-center measurements.

Spheres were poured in a hollow ~3 mm plastic cylinder (Figure 2) and the "fish-eggs" artifact was measured with the μ-CT system at the same position of the rotation stage and under the same settings prior to any specimen scan. Voxel scaling factor was calculated as the mean value of all center-to-center distances between spheres in contact; at least 10 pairs of spheres in contact were considered for each measurement. Rescaling was consistent between different scans, with an avg. of 0.9205 ± 0.0002 and a standard deviation of $2.6E-4$.

Surface determination

In previous studies, authors used a thresholding binarization of CT data with a subsequent surface smoothing of extracted voxels clusters [6], which potentially might introduce inaccuracies in extracted geometrical information due to discretization errors and partial volume effect. In this study, we use VGSTUDIO MAX 3.1 (abbreviated as "VG") to perform surface extraction with sub-voxel resolution. As a result, we extract the object surface with no intermediate binarization step.

The standard initial contour value is typically based on the ISO-50% global thresholding, selected as the arithmetic mean of the grey value corresponding to the background and the grey value corresponding to material peak in the grey-value histogram. This method was not applicable to our specimens, since no clear material peak was detected in the grey value histograms (top of Figure 3, for Mar300 15-45). This is caused by the high surface/volume ratio of the particles, which, for this combination of CT scan settings and amount of material in the specimens, induces a smooth transition of grey values between background and material peak. Consequently, global thresholding methods are not suitable for surface extraction of our datasets.

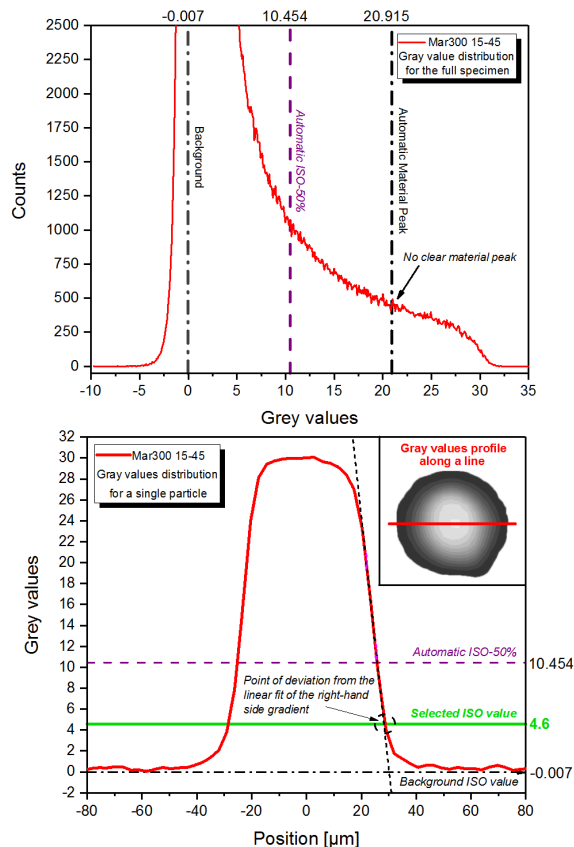


FIGURE 3. Mar300 15-45 dataset (Top) Automatic global thresholding ISO-50%; (Bottom) Local thresholding method, example for a single particle of the acquired dataset.

Therefore, a local thresholding method was chosen and its settings were tuned based on the LD measurements. In general, local thresholding methods can improve the measurement accuracy by partial compensation of beam hardening and other CT artifacts [7]. At the same time, local thresholding is more time consuming, settings-sensitive and none of the methods are suitable for all situations.

Our approach takes in consideration the development of the grey values local profile for particles of various size in every data set. The first derivative of the local profile is analyzed to find a sharp change in grey level denoting the edge and, consequently, a particle surface. Differently from Y. Tan et al. [7] approach, we always look for the minimum gradient between the ISO-50% calculated by VG and the ISO value corresponding to the background peak. An example of selection of the ISO value for the Mar300 15-45 is presented in Figure 3 (bottom). The point of deviation from the linear fit of the

right-hand side gradient corresponds to the min. of the first derivative of the local profile.

Surface determination is finally run on VG with the selected ISO value in a standard mode and, for comparison, with the automatic ISO-50% starting contour in a local adaptive mode (search distance of 4 voxels). This procedure is repeated for all three samples, which resulted in a total of six datasets.

Data analysis

For every dataset, two analysis procedures are performed: particles pores content estimation and size/morphology characterization.

A porosity analysis is performed in VG using the porosity/inclusion analysis module with a "threshold only" method. For every dataset, the threshold value was set to the corresponding ISO value as discussed in the previous section. For morphology/size analysis, a region of interest of ~10000 particles is selected in every dataset, and the particle surface is converted to a triangular mesh using "manual" mode with a volumetric sampling interval of 2 μm.

A particle analysis tool developed in-house in MATLAB was used to process the extracted particle surface and to calculate characteristics such as volume, surface area, principal dimensions, sphericity, bounding sphere, etc.

RESULTS

Particles porosity analysis

As expected, the amount of porosity in the selected specimens is almost negligible, due to the small average size of the particles [8] and to the high quality production processes (generally gas atomization for Maraging 300 and plasma atomization for Titanium CP).

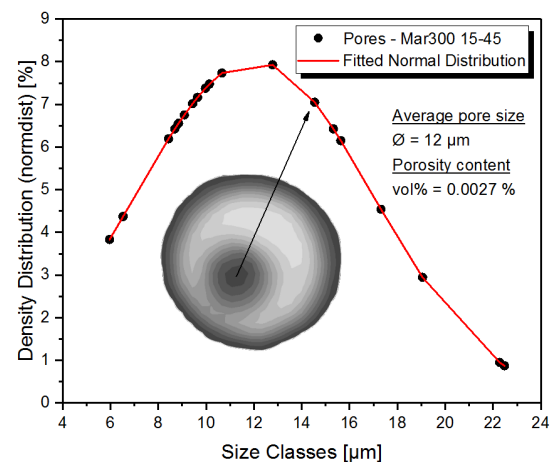


FIGURE 4. Normal distribution of the detected pores in the Mar300 15-45 powder specimen.

Only the Mar300 15-45 sample presents enough data points to derive a statistical analysis of the pores content, see Figure 4. The sample contained 63023 particles, but only 21 pores were detected with an average dimension of 12 μm . It must be considered that with a roughly 3 μm voxel size resolution, the internal porosity content might be underestimated, as reported by F. Bernier et al. [3], and a CT system with a higher resolution might provide a better estimation of the total amount of porosity.

Powder distribution analysis

Since particles were distributed on tape using dry spraying, there were multiple particles either touching each other or located too close to resolve them in CT scans. Therefore, prior to calculation of particle distribution and geometrical characteristics, we filtered out all possible artificial agglomerations.

Filtering is implemented in the MATLAB code based on principal dimensions (with $a \geq b \geq c$): only spheroids are selected (Figure 5, a & b) for size distribution estimation and shape analysis, corresponding to particles with principle dimensions ratios $b/a > 2/3$ and $c/b > 2/3$. Moreover, particles with a total volume below 8 voxels are also filtered out in 15-45 datasets, to avoid potential background noise [9] and as no particles of this size are expected in those specimens.

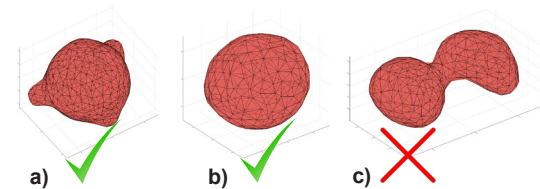


FIGURE 5. Examples of a) a particle with satellites, b) a spherical particle, and c) artificial particles agglomeration (subsequently filtered) for the Mar300 15-45 powder.

Even if supported by previous studies [2,9], this approach will limit further investigations on powder reuse and powder degradation. The proposed approach for particle filtration is hence applicable only for virgin high-quality powder. A new filtering method, or increased CT scan resolution is required for more advanced powder metrology.

Obtained cumulative distributions are presented in Figure 6. For every specimen we compare the LD measured distribution against the $\mu\text{-CT}$ results.

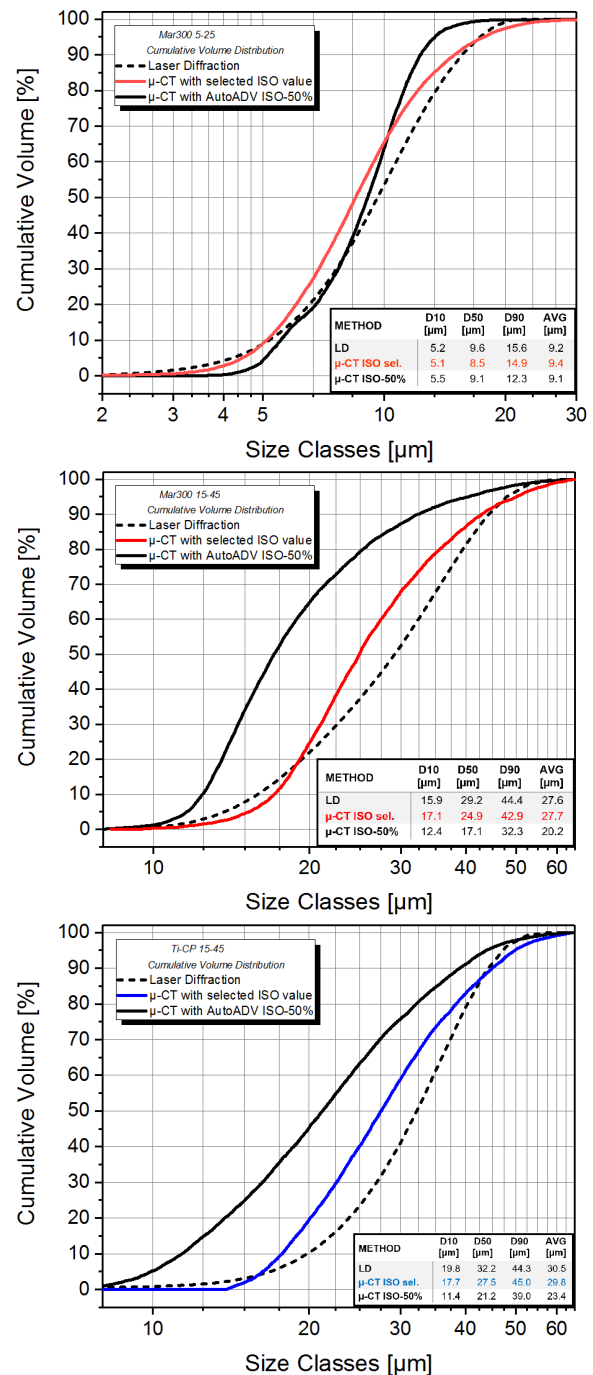


FIGURE 6. (Top) Mar300 5-25; (Middle) Mar300 15-45; (Bottom) Ti-CP 15-45; calculated distributions, comparison of LD vs $\mu\text{-CT}$.

$\mu\text{-CT}$ analysis of the Mar300 5-25 was performed without filtering on size, since a significant fraction of the particles volume falls below a total volume of 8 voxels. While circumscribed sphere measurements can still be accomplished on those small particles fractions, erroneous segmentation due to CT noise,

significant blurring and limited data points for surface extraction hamper the data analysis of the Mar300 5-25 specimen. For those reasons, we suggest that specimens with particles below ~8 μm should not be investigated with our current $\mu\text{-CT}$ setup, and no shape analysis has been performed on the Mar300 5-25 dataset.

On the other hand, implementation of the local thresholding was successful for all the specimens. Almost a perfect agreement with LD is found on the average particles size, and total size spread. Differences in the skewness of the distributions might be explained by the differences of the two measuring methods:

- Particle size is obtained as a deconvolution of the diffraction patterns for LD vs a 3D shape analysis (circumscribed sphere) for $\mu\text{-CT}$;
- Sample measured by LD contained $\gg 10000$ vs ~ 10000 particles measured with $\mu\text{-CT}$;
- Sample preparation is obtained with water dispersion plus sonication for LD vs dry spraying for $\mu\text{-CT}$.

As has been reported in different studies [1,10], skewness and shape of the powder distribution are highly dependent on the instrument, which must be carefully selected based on powder characteristics and application.

One clear outcome of this investigation is that standard global thresholding ISO-50% method with this $\mu\text{-CT}$ setup fails to provide a reliable powder distribution, even with local adaptive surface determination mode: overestimation of the ISO value for surface determination will always lead to a huge underestimation of the particles size.

Powder shape analysis

Shape is a critical aspect for AM metal powders, since shape will influence the flowability and its apparent/tapped density. Different shape parameters have been developed overtime to describe powders, mainly taking in consideration only the 2D shape that might result from an optical/SEM microscopy or laser beam based measurement. Qualitative descriptions of powder particles have been as well standardized [11], and out of all possible metrics, circularity and aspect ratio are the most commonly used shape factors for AM powder. A single 2D shape factor cannot completely describe a particle shape, and assumptions must normally be made for every specimen.

The power of $\mu\text{-CT}$ analyses relies on the fact that a full 3D shape is acquired, providing domain specialists with comprehensive

information which potentially can be integrated into multi-criteria decision making approaches and advanced SLM process simulations. As an example, for every powder specimen, 3D shape factors like roundness, sphericity and compactness can be calculated using our in-house MATLAB code. Sphericity results are summarized in Figure 7 for both Mar300 15-45 and Ti-CP 15-45 samples.

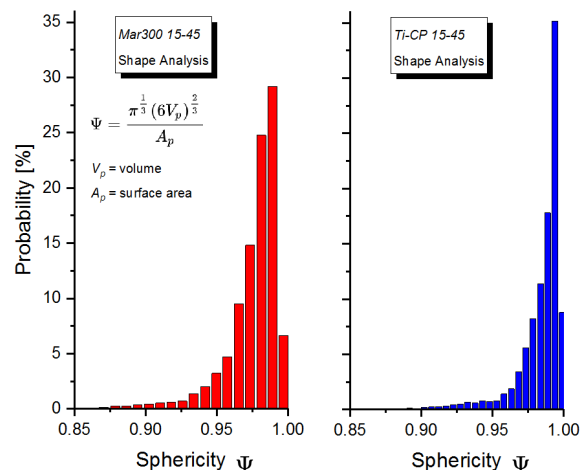


FIGURE 7. Sphericity index for Mar300 15-45 and Ti-CP 15-45.

As expected, a shape analysis results in high sphericity for both specimens, with Ti-CP being overall slightly more spherical.

New 3D shape indicators, such as the possibility to count and describe particles satellites, as well as more advanced 3D shape analyses [2] will be the focus of future work.

PRELIMINARY STUDY ON MULTIMATERIAL $\mu\text{-CT}$ POWDER ANALYSIS

A preliminary study is hereby introduced to explore more advanced applications of CT to metallic powder characterization. Besides powder porosity, distribution and shape, $\mu\text{-CT}$ has already been used to detect cross-contamination of powder batches either in the final printed part [12] or in the raw material state [13]. Although detection was successful for both cases, a precise assessment was not possible because of the difficulties in resolving touching particles and in the multi-material surface determination.

To overcome those limitations, a new approach is developed and implemented in MATLAB. The main intuition relies on the fact that even if no well-defined and separated material peaks are present on the scans, a thresholding ISO value can be selected looking at the local gray

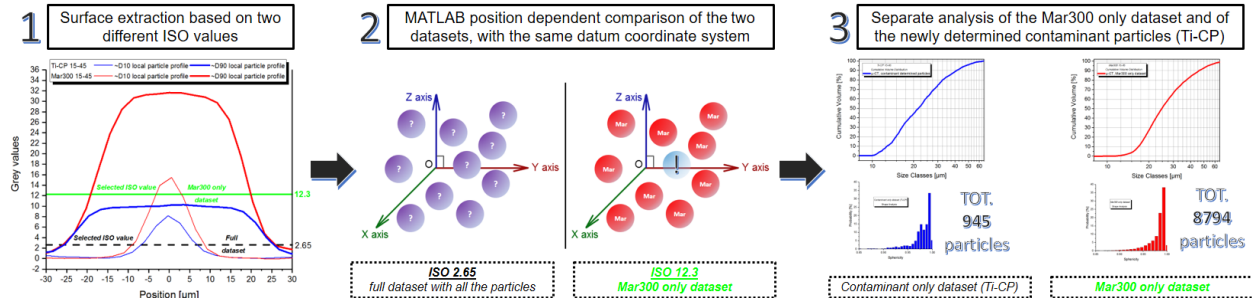


FIGURE 8. Schematic of the multi-material μ -CT powder analysis to detect cross-contamination of powder batches; example for an artificial contaminated Mar300 15-45 specimen with 10 vol% Ti-CP.

values profile to iteratively isolate the contaminant from the main powder batch. To confirm this assumption, an artificial contamination is produced on a Mar300 15-45 specimen, with 10 vol% amount of Ti-CP. The full analysis process is schematized in Figure 8. A total contamination of 9.7 vol% of Ti-CP is retrieved with the implemented code, in good agreement with the prepared sample. Undergoing efforts are focused on the statistical validation of the implemented method, comparing results at different percentages of artificial contamination for different materials. CT users must be aware that powders of materials with similar densities will not be distinguished with current CT machine setups. Nonetheless, theoretically, even oxides of the same material could be distinguished if the difference in X-ray attenuation is high enough, and μ -CT analysis could consequently investigate not only powder cross-contamination, but also powder degradation after sieving and reuse.

CONCLUSIONS

After adequate scaling error compensation, the acquired data set demonstrates how μ -CT could be a viable metrological technique to derive, with one measurement, primary characteristics of PBF starting materials. For distribution and shape analyses, special care must be employed on the ISO value determination prior to surface extraction. The current main limitation relies on the finite focal spot size of the μ -CT X-ray source and consequently on the limited spatial resolution. Statistical validation of the proposed local thresholding method for surface determination must be done at different μ -CT scan settings and with different powder specimens.

The potential for detecting powder cross-contamination and eventually powder degradation has been introduced and will be the main effort in future studies.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] Sutton AT, Kriewall CS, Leu MC, Newkirk JW. Powder characterisation techniques and effects of powder characteristics on part properties in powder-bed fusion processes. *Virtual and Physical Prototyping*. 2017 Jan 2;12(1):3–29.
- [2] Su, D., and W. M. Yan. "3D Characterization of General-Shape Sand Particles Using Microfocus X-Ray Computed Tomography and Spherical Harmonic Functions, and Particle Regeneration Using Multivariate Random Vector." *Powder Technology* 323 (January 1, 2018): 8–23.
- [3] Bernier, Fabrice, Rui Tahara, and Mathieu Gendron. "Additive Manufacturing Powder Feedstock Characterization Using X-Ray Tomography." *Metal Powder Report*, February 2018.
- [4] Stolfi, A., and L. De Chiffre. "3D Artefact for Concurrent Scale Calibration in Computed Tomography." *CIRP Annals* 65, no. 1 (2016): 499–502.
- [5] Müller P, Hiller J, Dai Y, Andreasen JL, Hansen HN, De Chiffre L. Quantitative analysis of scaling error compensation methods in dimensional X-ray computed tomography. *CIRP Journal of Manufacturing Science and Technology*. 2015 Aug;10:68–76.
- [6] Slotwinski, JA, EJ Garboczi, PE Stutzman, CF Ferraris, SS Watson, and MA Peltz. "Characterization of Metal Powders Used for Additive Manufacturing." *Journal of Research of the National Institute of Standards and Technology* 119 (September 16, 2014): 460–93.
- [7] Tan Y, Kiekens K, Kruth J P, Voet A and Dewulf W. Material dependent thresholding for dimensional x-ray computed tomography. *Int. Symp. on Digital Industrial Radiology and Computed Tomography* (Berlin, Germany, 2011).
- [8] Guo, Rui-Peng, Lei Xu, Bernie Ya-Ping Zong, and Rui Yang. "Characterization of Prealloyed Ti–6Al–4V Powders from EIGA and PREP Process and Mechanical Properties of HIPed Powder Compacts." *Acta Metallurgica Sinica (English Letters)* 30, no. 8 (August 2017): 735–44.
- [9] Pavan, Michele, Tom Craeghs, Raf Verhelst, Olivier Ducatteeuw, Jean-Pierre Kruth, and Wim Dewulf. "CT-Based Quality Control of Laser Sintering of Polymers." *Case Studies in Nondestructive Testing and Evaluation* 6 (November 2016): 62–68.
- [10] Iacocca, R. G., and R. M. German. "A comparison of powder particle size measuring instruments." *International journal of powder metallurgy* 33.8 (1997): 35–48.
- [11] ASTM B243-17. *Standard Terminology of Powder Metallurgy*, ASTM International, West Conshohocken, PA, 2017.
- [12] Jamshidinia, M, P Boulware, J Marchal, H Mendoza, L Cronley, S Kelly, and S Newhouse. "In-Process Monitoring of Cross Contamination in Laser Powder Bed Fusion (L-PBF) Additive Manufacturing (AM)." In *Solid Freeform Fabrication 2016*, 15, 2016.
- [13] Brandão, Ana D., Romain Gerard, Johannes Gumpinger, Stefano Beretta, Advenit Makaya, Laurent Pambaguian, and Tommaso Ghidini. "Challenges in Additive Manufacturing of Space Parts: Powder Feedstock Cross-Contamination and Its Impact on End Products." *Materials* 10, no. 5 (May 12, 2017).

Adaptive abrasive finishing of AM components through in-process monitoring and tool-path corrections

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INTRODUCTION

Additive manufacturing (AM) has had a significant impact on high-value and precision based manufacturing industries such as aerospace, automotive and medical. Recent research and development trends, both in the adopters of AM processes, and those who develop the processes and machinery themselves, highlights poor surface finish as one of the most significant challenges preventing the large-scale uptake and integration of AM into state-of-the-art high value manufacturing process chains. The effect of the poor surface finish, that is typical of as-built AM surfaces, is a reduction in fatigue life. It has been proven that improving the surface roughness to remove the surface asperities associated with AM build process and materials greatly improves the fatigue life of components (1). Machining has shown to provide the greatest improvement to fatigue life when compared to as-built and shot-peened components (fig 1). Other benefits for a reduction is surface roughness on additive surfaces include improved fluid flow (2), lower frictional surfaces (3).

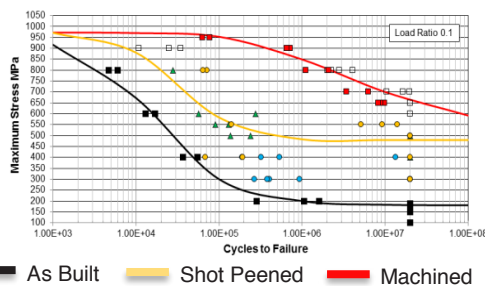


FIGURE 1. Fatigue life of post-processing routines for AM components (1).

Surface topography of typical as-built parts

Both the build process and material stock can significantly impact the surface roughness and dimensional fidelity of the as-built parts. Electron Beam Melting (EBM) may produce parts with a surface roughness ranging from 25-50 μm S_a ($\lambda_c=2500\mu\text{m}$). Selective Laser Melting (SLM) or Laser Powder-Bed Fusion (L-PBF) can produce similar parts with surfaces ranging from 10-15 μm

S_a ($\lambda_c=2500\mu\text{m}$). These surface topographies may have peak-valley height differences (S_z) of approximately 100-200 μm for SLM parts, and 200-400 μm for EBM parts. Geometric tolerances (nominal dimensions differing from as-built dimensions) may vary in the order of 100s of μm .

Dimensional deviations from design of typical as-built parts

In addition to deviation in as-built surface from the nominal design, variations in AM processes can cause dimensional errors as well. Factors such as anomalies in powder flow, scanning mirror accuracy (in L-PBF systems), and build parameters can affect dimensional accuracy of the final part. There may, for example, be areas of the part with excess material. This additional material must therefore also be considered when finishing components if there are critical dimensions with low tolerances in areas being finished.

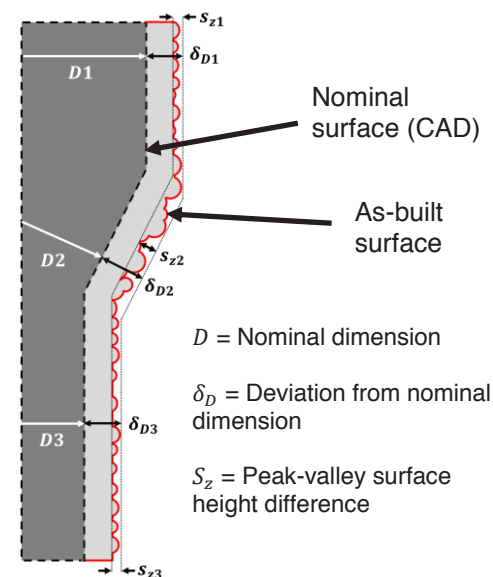


FIGURE 2. Topographical (S_z) and dimensional (δ_D) contributions to surface height errors in AM components

Surface finishing of AM components

Improvements to the surface roughness of metallic AM parts are often achieved through abrasive finishing, where abrasive media is used to remove surface asperities such as semi-melted powder particles (fig 3).

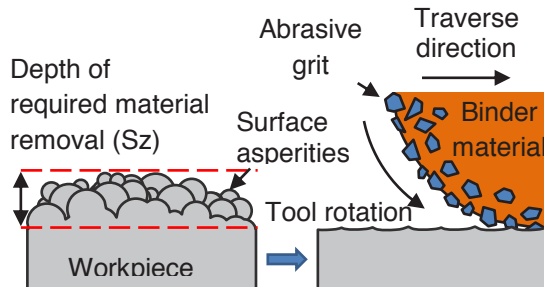


FIGURE 3. Abrasive finishing material removal on an AM surface.

Aside from the time and cost implications of carrying out this process manually, repeatability is low and it is not possible to scale the process to production volumes without heavy investment in training new labourers to a high level of skill. Furthermore, to achieve a desired finish whilst maintaining adherence to part dimensions and tolerances, variations in planned material removal across the entire part must be accommodated. In addition, abrasive finishing (linishing) tools can conform to the component surface, minimising faceted surfaces and hence retaining form. Where machining marks occur, they can be imparted onto the component in the direction of loading, improving post-processed fatigue strength.

Automation of post-processing of AM parts

Without investing in time consuming amendments to measured 3D part data, obtained for example through point-cloud measurement and reverse-engineering, machining toolpaths from part CAD may not reflect the real geometry of the part. Therefore “open-loop” toolpath planning with correction for these geometrical may not follow the real surface geometry of the part resulting in inconsistent machining forces, and hence inconsistent finishes.

ROBOT TOOLPATH ADJUSTMENTS USING FORCE-TORQUE FEEDBACK

By incorporating a robotic arm utilising a force-torque sensor, a machining operation can be defined with a target force for the tool to exert upon the workpiece. By comparing this reference (target) force with the force measured by the force-torque sensor (resolved in a direction

defined by the programmer), the robot’s planned motion path can be dynamically updated to ensure that the measured contact force closely matches the targeted optimum force required for the process (fig 4).

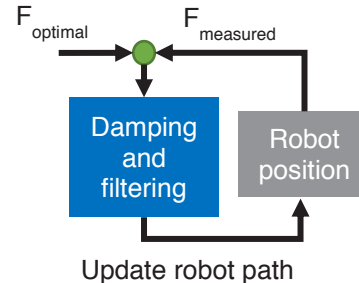


FIGURE 4. Force feedback control loop

PROCESS PARAMETER OPTIMISATION

By analysing the surface before post-processing, material removal requirements can be defined such that the resultant surface will a) have a surface finish within requirements (i.e. a target topography), and b) the resultant part dimensions will fall within design limits (i.e. a target dimension).

Topography driven parameter optimisation

It is known that different areas on a 3D printed component may exhibit different surface roughnesses. This may be heavily influenced by the types of geometries on the part. For example, overhangs on SLM components may exhibit roughnesses approximately twice that of surfaces which are parallel (or close to) the build plate (4). These surfaces may require increased material removal as insufficient material removal may result in surface morphologies such as pitting, where the initial surface topography has not been completely removed.

A knowledge base of post-processing parameters for abrasive finishing has been developed where post-processed surface conditions such as areal roughness (S_a) and maximum height (S_z) are related to machining parameters, from known initial surface conditions (S_a and S_z). From this database optimum machining forces and feed speeds can be calculated to remove a known amount of material, and achieve a target surface roughness.

To achieve a polished surface finish the following process has been developed (fig 5):

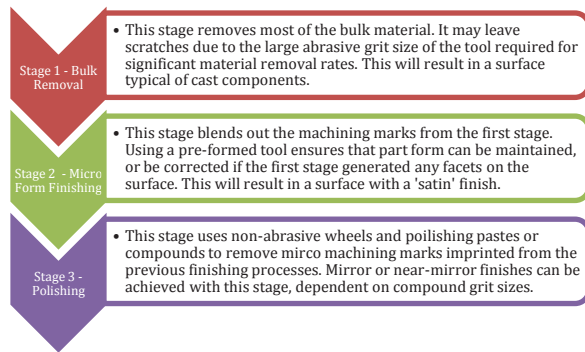


FIGURE 5. Progressive abrasive finishing steps to achieve polished finishes from rough as-built surfaces.

Abrasive media is often provided with a grade or specification relating to the size of abrasive grits/grains. This abrasive grit size will directly affect the achievable surface roughness after post-processing, as larger grit sizes result in deeper machining marks, leading to higher roughnesses. Likewise for smaller grit sizes, shallower machining marks lead to smoother surfaces.

Using grit sizes greater than the typical size of surface asperities has not shown a significant improvement in material removal when compared to grit sizes of a similar size to surface asperities. Using coarser grits however does result in a rougher surface finish which may require further processing stages using finer grits. Figure 6 describes the relationship between grit size and achievable surface finish after all initial surface asperities have been removed. The processing stages described in figure 5 are also labelled.

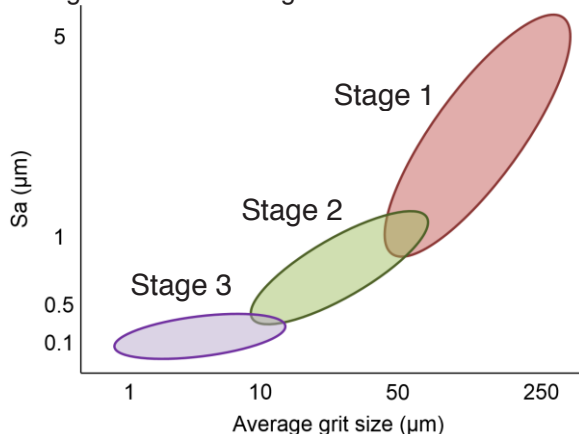


FIGURE 6. Surface finishes achievable with a range of grit sizes.

Dimension driven parameter optimisation

To further optimise the entire post-processing toolpath, machining parameters can be varied throughout a robot toolpath to achieve optimum material removal rates for the various geometric deviations seen across an as-built component. By characterising the deviation from the nominal as-designed surface, the material removal required to achieve a good surface finish can be further optimised to also machine the component to within designed dimensional tolerances.

A relationship between two key process variables can be established for a specific process, in terms of tool characteristics (including geometry, spindle speed, and abrasive grit) and component geometry, versus material removal rates. In general, low feed rates (or higher spindle speeds) will result in more material removal. Conversely, high feed rates (or lower spindle speeds) will remove less material. Similarly, higher forces will remove more material, however there are limits to the material removal when applying higher forces as the abrasive grits can only remove depth of material similar to their size for every rotation of the tool. These relationships are depicted in figure 7 below.

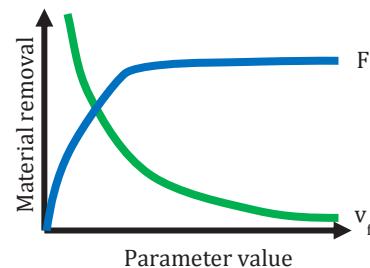


FIGURE 7. Trends for material removal vs force applied (F) and feedrate (v_f).

RESULTS

The following approach has been applied to surface process EBM dogbones. The components will be used as part of ADDMAN, a CleanSky H2020 funded project which aims to understand how the fatigue life of AM components is affected by various surface finishing techniques.

The as-built surface of the dogbones are depicted in figure 8, the average S_a and S_z are $30\mu\text{m}$ and $289\mu\text{m}$ respectively ($\lambda_c=2500\mu\text{m}$, measurement taken on an Alicona InfiniteFocus SL with a 10x objective).



FIGURE 8. As-Built EBM dogbone

The components were built on an Arcam A2XX, in Ti-6Al-4V. The parts were subsequently put through a hot isostatic pressing (HIP) cycle to improve their density and remove sub-surface pores. As the dogbones exhibited curved geometries, tools have been used that can conform to these somewhat complex surfaces. These included felt backed aluminium oxide flap wheels for the bulk removal stage, non-woven unitised wheels for the micro form finishing, and cotton flap wheels with polishing compounds for the polishing stage. A p120 grit flap wheel was used during the bulk removal stage which equates to average particle sizes of approximately $100\mu\text{m}$.

Using a nominal straight-line toolpath, a relationship was found between material removal and force applied by the robot, for a constant feed rate and spindle speed. This relationship was determined for each of the tool types and grit sizes used throughout the process.

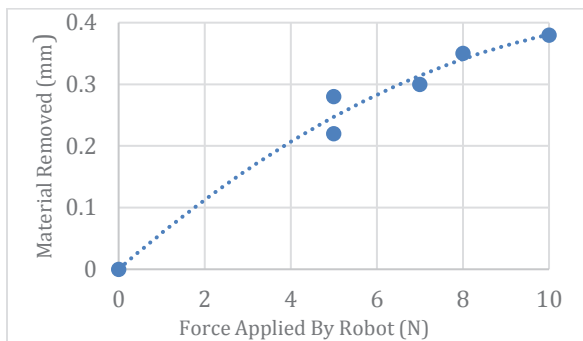


FIGURE 9. Force applied vs material removed for p120 grit 30x15mm aluminium oxide flapwheel, spindle speed = 12,000rpm, feed rate = 20mm/s

At high forces ($F > 10\text{N}$) there were diminishing returns for material removal, and increased tool wear. As previously mentioned, this relationship varies by tool type and abrasive grit size, however there was a general trend for all tool types used for excessive forces to result in accelerated tool wear and little increase in material removal (as depicted in figure 7). A force of 5N was used and a relationship between feed rate and material removal was obtained for a fixed spindle speed:

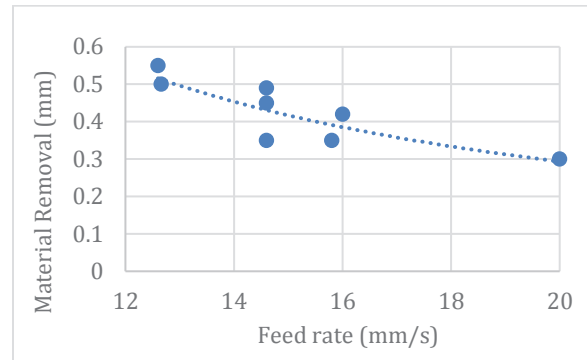


FIGURE 10. Feedrate vs Material Removed for p120 grit 30x15mm aluminium oxide flapwheel, force applied = 5N, spindle speed = 12,000rpm

By utilising these models it was possible to predict the material removal for a fixed force and a known feedrate for a single pass over the component. The requirement for these parts was a very fine surface finish, to retain as high a neck diameter as possible and to induce machining marks parallel to the loading direction used in the subsequent fatigue tests. By analysing the initial surface roughness and peak-valley height values the minimum amount of material removal needed to achieve a fine surface finish (after removing all initial surface asperities) could be determined. In this case, approximately 1mm of material removal was required ($500\mu\text{m}$ on either side of the neck). By re-measuring the neck dimension and updating the feed rate for each pass, it was possible to remove only the amount of material required, and generate surfaces with areal roughnesses $< 100\text{nm}$ ($A_c = 200\mu\text{m}$). Figure 11 shows the relationship between predicted and measured neck dimensions for 11 specimens.



FIGURE 11 - Predicted vs Measured dimensions for 11 dogbone specimens

The surface topographies of post-processed components were then measured using focus variation, confocal and interferometry techniques (using a Sensofar S Mart sensor) to characterise the surfaces. The dogbones which had an average initial surface roughness of $30\mu\text{m}$ ($\lambda_c = 2500\mu\text{m}$) were post-processed and had final surface roughnesses as low as $0.08\mu\text{m}$ ($\lambda_c = 200\mu\text{m}$) (fig 12.).

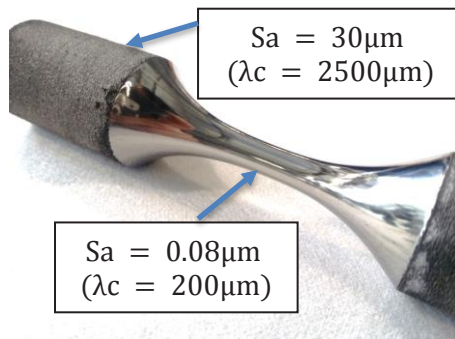


FIGURE 12. Post-processed component

CONCLUSIONS

Controlled material removal was made possible by the characterisation of the relationship between abrasive finishing process parameters and the amount of material removed for a given material. By incorporating a force-torque feedback sensor into a robotic abrasive finishing system, the key process variables that had an effect on material removal rates could be monitored and dynamically updated during a finishing process. By employing this method, processing parameters were selected to remove a known amount of material, and measurements across 11 separate samples showed good agreement between the models used and the actual amount of material removed, with most samples showing a measured material removal depth within $50\mu\text{m}$ of prediction (for a target material removal depth of $1000\mu\text{m}$).

Progressively finer grits and varying tool types were included in this approach, creating a multi-stage optimised process removing only the amount of material required to ensure the target surface finish was achieved.

REFERENCES

1. *Assessment of "As-Printed", Machined & Post Processed Additive Layer Manufactured (ALM) Ti-6Al-4V for Aerospace Applications.* **S. L. Jenkins, D.**

P. Davies, J. P. Fuhr, S. McArthur. Montreal : s.n., 2017. ICSP-13.

2. *Roughness Effects on Flow and Heat Transfer for Additively Manufactured Channels.* **Curtis K. Stimpson, Jacob C. Snyder and Karen A. Thole.** s.l. : Proceedings of ASME Turbo Expo 2015: Turbine Technical Conference and Exposition , 2015. GT2015-43940.

3. *The Influence of Roughness on the Wear and Friction Coefficient under dry and lubricated sliding.* **Riyadh A. Al-Samarai, Haftirman, Khiarel Rafezi Ahmad, ,Y. Al-Douri.** 4, s.l. : International Journal of Scientific & Engineering Research, 2012, Vol. 3.

4. *Effect of process parameters on the surface roughness of overhanging structures in laser powder bed fusion additive manufacturing.* **Jason C. Fox, SHawn P. Molyan, Brandon M. Lane.** 2016. CIRP CSI.

Cleanliness of Parts Manufactured Via Metal Laser Powder Bed Fusion (LPBF)

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OVERVIEW

The Kansas City National Security Campus (KCNSC) manufactured additive metal components for a customer focusing on low cost and rapid through put. However, when their customer evaluated the parts for critical cleanliness, the results surprised both the manufacturer and customer; the parts contained hydrocarbon contamination from metalworking fluids used in post-processing. Conclusions were reached that additively manufactured (AM) metal parts are porous and must include the addition of a vacuum oven bake cycle during cleaning to remove traditional post-processing contaminants. KCNSC took this opportunity to further evaluate their aqueous cleaning process and demonstrate that additively manufactured parts can achieve critical cleanliness requirements without exercising a vacuum oven bake cycle. Additional efforts have also been executed to begin evaluation of cleanliness of as manufactured AM surfaces relative to traditional material.

Background

In the very early stages of metal laser powder bed fusion technology at the KCNSC, circa 2014-15, mock components were manufactured via metal AM to mimic traditionally manufactured components while focusing on overall lower cost, faster lead time and reduced requirements. As product scope grew to more critical applications, the customer placed components in a vacuum oven bake cycle to evaluate critical cleanliness by residual gas analysis (RGA). During this cycle foreign contaminants were extracted from the evaluated component. The material removed was mostly an oil based cutting fluid used during machining which was not properly cleaned from the restricted access interior volume of the part during production of the developmental hardware. The initial conclusion was that the metal additively manufactured components have an interconnected network of porosity that was harboring the metalworking fluid. It was proposed that the only way to remove

hydrocarbon contamination from additively manufactured components was to execute a vacuum oven bake cycle on the components with temperatures in excess of 300 degrees Celsius and vacuum levels in excess of 10^{-4} Torr. KCNSC took this opportunity to gain a deeper understanding of the cleanliness level of the components, comparing results from a newly developed cleaning cycle both with and without a vacuum oven cycle. Additional steps have been taken to evaluate mass loss of as-AM samples compared to traditional billet material during the ultrasonic cleaning process.

Results

KCNSC evaluated 42 components under a controlled cleaning process, both with and without a vacuum oven bake to understand the level of hydrocarbon contamination potentially retained on components. After the cleaning cycles, single parts were ultra-sonicated in a beaker of ultrapure methylene chloride and residuals were examined for hydrocarbon content. A total of 21 pieces were cleaned with a standard cleaning process and the remaining 21 pieces were cleaned with the standard cleaning process including a vacuum oven bake cycle. Extraction residues were analyzed via Fourier-transform infrared spectroscopy for quantification. Analysis of the 2-sample T-test indicated no statistically significant difference in levels of hydrocarbons contained within a part that has or has not undergone a vacuum oven bake cycle. Practically speaking, vacuum oven baked parts do have a tighter distribution and smaller average value of quantified hydrocarbons in micrograms, but both distributions reside in the same statistical space, Figure 1.

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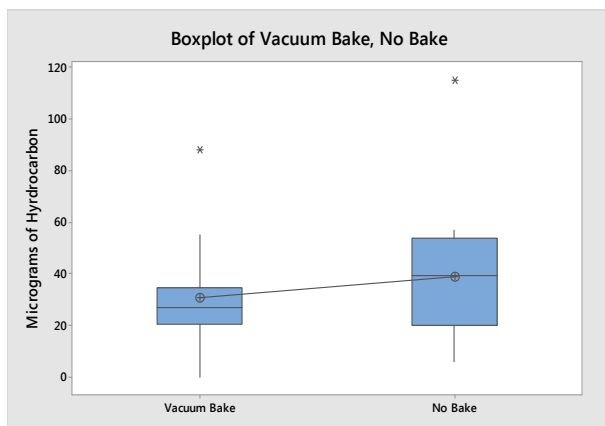


FIGURE 1. Boxplots of hydrocarbon content extracted from components with and without a vacuum oven bake cycle.

Additional Background

While reviewing components for cleanliness of hydrocarbons it was observed during ultrasonic cleaning cycles components were losing on the order of 10's of milligrams of overall mass. The components evaluated are machined on the outside surfaces but have as-AM surfaces internally in a chamber with only 0.250" access holes for bulk powder removal. Access holes allow powder to be removed but do not allow for post-processing of the internal surfaces. To better understand what was happening with the as-AM internal surfaces, AM metal coupons were manufactured and were post-processed to gain insight on mass loss from components. Control billet plate samples of 316L were also cleaned and observed before and after machining. Mass loss of the samples were quantified by total mass loss (mg) and by mass loss (mg) per surface area (mm²). As built AM samples and billet samples measure approximately 2" X 3" X .250", while machined samples measured 1.975" X 2.950" X .180" as seen in Figure 2.

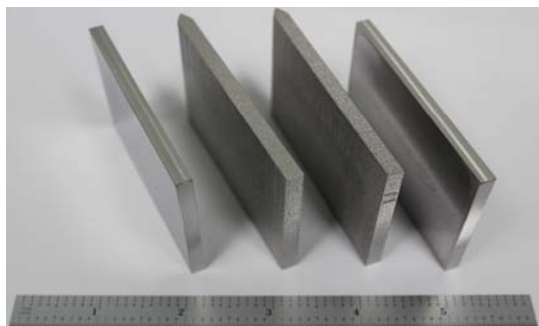


FIGURE 2. 316L samples of: machined billet, blasted AM, vibratory deburred AM and machined AM.

Additional Results

As-built AM samples approach a steady state mass loss after three 10 minute ultrasonic cleaning cycles, at a total of 20 mg mass loss or 0.0022 mg/mm². However, the first three cleaning cycles remove a total of 951 mg. The billet samples reach steady state after a single cleaning cycle and lose only an average of 6 mg or 0.00054 mg/mm² as recorded over five cleaning cycles. Both machined AM and machined billet samples show no detectable mass losses over multiple cleaning cycles. AM samples that underwent vibratory finishing showed an average of 5 mg total mass loss for their fourth and fifth cleaning cycles while blasted AM samples lost an average of 2 mg per cleaning cycle, most importantly stabilizing after their first cleaning cycle. Data can be viewed in the summary table below.

TABLE 1. Mass loss per cleaning cycle of multiple material samples.

Total Mass Loss per Cleaning Cycle of Samples (mg)					
Sample	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
As Built Metal AM	810	98	42	20	17
Billet Plate	36	7	7	3	5
Machined AM	ND	ND	ND	ND	ND
Machined Billet	ND	ND	ND	ND	ND
Vibratory Metal AM	440	29	12	4	6
Blasted Metal AM	13	1	2	2	4

Future Work

KCNCS will pursue evaluation of variable ultrasonic aqueous cleaning to successfully remove potentially vulnerable material in a more efficient manner. Additionally, the use of a liquid-borne particle counter system will be used to better quantify the potential vulnerable particulate.

Acknowledgements

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SURFACE TEXTURE CHARACTERIZATION AND OPTIMIZATION OF METAL ADDITIVE MANUFACTURING-PRODUCED COMPONENTS

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INTRODUCTION

The demand for additive manufactured (AM) components is growing at an accelerated rate. AM is not just an ideal route to produce rapid and practical prototypes, but it has also opened the door to produce truly free-form components. Nevertheless, AM-built components have an intrinsic problem; their surfaces are extremely rough, packed with multiple layers of partially melted/sintered powder and significant surface and near-surface defects. The most common defects that are encountered on AM components include: partially sintered/melted powder, v-notches, surface and near-surface porosity, lack of fusion, lack of penetration, delamination, slumping, and others.[1–4] These defects usually make the components susceptible to poor mechanical performance, early failure, and corrosion. Consequently, post-processing and surface finishing operations of the AM-built components are necessary to obtain a functional part. Moreover, due to the extreme complexity of the AM-produced parts, traditional post-processing surface finishing is not a viable option in many cases. Therefore, there is a latent need for surface finishing techniques capable of improving the surface texture of the AM-produced components, while also improving their mechanical properties. However, due to the distinctive characteristics of these AM surface textures, it is imperative to take into consideration the “anatomy” of the surfaces in order to do achieve their accurate characterization and optimization.

In this paper, we will discuss the main features of the surface texture characteristics of AM components (Figure 1) and the best practices to optimize and characterize them, based on their structure. The parameters affecting the surface texture during the building process will also be discussed. Different examples of surface finishing (post-processing) employed to improve the texture of AM components surfaces will be discussed.

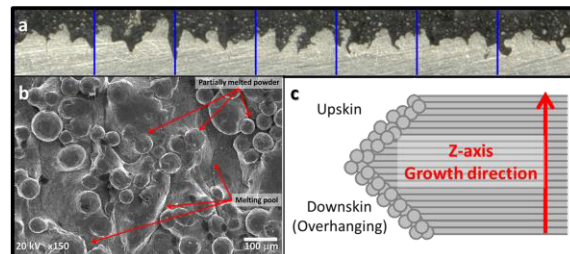


FIGURE 1. Simplified surface anatomy of an AM-built component parallel to the direction of growth (z-axis) showing the complexity of the AM-produced surface texture: (a) side view of the surface texture showing the partially melted/sintered powder, v-notches and near-surface porosity; (b) top view of the surface texture showing the partially melted/sintered powder and the melting pool surface features, typical of powder bed fusion AM surfaces; (c) a simplified diagram showing different regions on an AM-built components which will show an unique surface texture within the same component based on their orientation relative to the growth direction.

SURFACE TEXTURE OF AM COMPONENTS

The surface texture of a 3-D printed component built by the powder bed melting/sintering method is extremely complex. The printing process imparts particular features on the surface that are completely associated, and can be correlated, to the printing parameters. The surface texture features of these components are unlike those observed on traditional subtractive metal parts, such as simple periodic machining marks. However, despite the fact that different 3-D printing machines produce different surface textures, there are common features present in almost all of the components' surfaces.

Printing parameters such as the powder size, source type, hatch spacing, scan time, contour, source power, type of material, layer thickness,

the environment in the chamber, the orientation of the build, and many others will create specific features on the surface texture.[5–11]

Usually, the surface texture of AM-built components shows four main features that can be identified by taking a closer look at the morphology of the surface (Figure 1). The most predominant surface texture feature is located on the XZ and YZ planes (with the Z axis as the build direction) of the components relative to the powder bed (vertical surface), while the other three are located on planes that are nearly parallel to the powder bed (horizontal surface). [5,12–14] The vertical surface is the surface exposed and in contact with the powder in the bed. If there is an inclination, this surface will show the staircase feature, with two possible features, the upskin and the downskin (overhanging) surface. The horizontal surfaces are the ones on the top and bottom of the components. The discussion of this paper will focus on the optimization of the vertical surface, since it is the roughest and predominant texture on a component.

SURFACE TEXTURE OPTIMIZATION

There are several technologies that can be used to planarize the surface textures of AM components. Each technology produces an optimized surface texture with distinctive features, but the most successful of them produces mirror-like surfaces. The Extreme ISF[®] process is one of the surface finishing technologies capable of producing a mirror-like finishing, while improving the mechanical performance for the components. The basis of the process is a chemically accelerated vibratory finishing (CAVF) developed by REM Chemicals, Inc. The ISF[®] (isotropic superfinishing) process was patented and developed by REM Surface Engineering[®] in the 1980's and it has continued to evolve since then, gaining great acceptance in the aerospace, medical, automotive, motorsport, and power generation field.[15–20]

REM has developed advancements to its ISF[®] technology to address the more demanding requirements of the AM industry (the Extreme ISF[®] Process). This technology has been developed for use on Ti-6Al-4V components and has shown remarkable preliminary results, including superior tensile strength and bending fatigue properties. The Extreme ISF[®] process has demonstrated to be one of the best approaches to improve the mechanical

performance of AM-built components by a surface finishing operation. The process works by chemically-activating the surface in a vibratory bowl in contact with media, and due to a mechanical stimulus of the media the surface peaks and defects are removed. [20–22] This process targets the removal of the loosely-attached and partially melted/sintered powder particles on the surface. Through the use of this technology, REM has demonstrated the ability to remove > 0.02" of material from the surface of Ti-6Al-4V components with a high degree of uniformity and absolute process repeatability.

The technology has also eliminated all surface and near-surface defects in Ti-6Al-4V AM components while significantly reducing the surface roughness and waviness of the components (Figure 2). One of the limitations of vibratory finishing with abrasive media is that the media employed has to reach the surface with a certain force to create an abrasive action and eliminate the peaks. In cases where the surfaces are inaccessible, the media cannot achieve an effective contact; thus, no effective action occurs. However, this is not entirely the case for the CAVF, where the chemistry homogeneously reaches the entirety of the surface, and the media just needs to contact the surface with a gentle rubbing action to remove the chemically-activated metal surface.



FIGURE 2. 3D-printed Bike-post component designed by Spencer Wright and built by AddAero using an Arcam A2X, before (left) and after (right) of the Extreme ISF[®] Process.

This simple, yet elegant, approach considerably reduces the heterogeneous surface removal faced by the abrasive finishing, such as rounding and edging problems shown by high energy, and tumbling finishing processes. Furthermore, the Extreme ISF[®] Process has shown a dramatic effect on the mechanical performance of AM components by eliminating surface v-notches and near-surface defects. Final surface finishes with $Ra < 32 \mu\text{m}$ are commonly achieved, especially if the surface is accessible to the media, and finishes lower than $8 \mu\text{m}$ are possible. In addition, the elimination of the surface and near-surface defects has resulted in substantial increases in the components tensile strength and high cycle bending fatigue resistance, as compared to as-printed components.

CASE STUDY

The mechanical performance of AM-built components is of vital importance for many industries due to the devastating implications of early failures. In most cases, the culprit of all failures resides in the surface, and this is not an exception for AM-built components. Surface defects such as v-notches, partially melted/sintered powder, microcracks and porosities are very common on the AM-built surfaces, and they will prompt early mechanical failure under stress. A mirror-like surface finishing should significantly improve the mechanical properties of the component, thus improving its fatigue life, which is essential so that these components can be approved for use in many applications.

In this case study, we surface finished an AM-built (EBM) bike post designed by Spencer Wright and built by AddAero (Figure 2).[23] The surface texture optimization for this component was performed with the intention of improving its fatigue life; therefore, an optimal mirror-like surface finishing was targeted for this component. The surface finishing was first attempted with a micro-machining process, which showed early failure when compared to the as-built component.[23,24] The part was beautifully polished by abrasive action to a mirror-like surface, but the design of the part did not account for the metal removal needed to achieve a polished surface, hence the polished component was significantly thinner than the as-built. Moreover, when the polished specimen was analyzed under the microscope, v-notches were identified on the surface.

A second set of parts was built and this time the design was altered to account for a 0.02" of metal removal. The initial Ra (average surface roughness, $\lambda_c = 800 \mu\text{m}$, or 0.03 in and $\lambda_e = 12.5 \mu\text{m}$, or 0.5 in) was around $1300 \mu\text{m}$. The part was processed by the Extreme ISF[®], showing a remarkably improved surface with a mirror-like surface finishing and a $Ra 35 \mu\text{m}$ (Figure 3). The fatigue experiments are in process, but tensile strength and fatigue data of AM-built bending fatigue specimens (ASTM E8 and E466) show a significant improvement on the fatigue life of the parts processed by Extreme ISF[®]. [21,25,26]

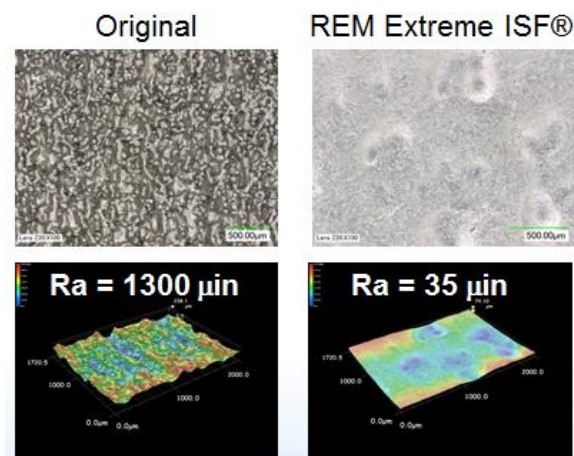


FIGURE 3. Optical micrograph and 3D-representation of the surface of a Ti-6Al-4V component built by EBM with an Arcam A2X, before (left) and after (right) of the Extreme ISF[®] Process.

CONCLUSION

The Extreme ISF[®] process has demonstrated to significantly improve the surface texture of AM-built components. Tensile strength and bending fatigue (axial tensile and rotating) testing of Extreme ISF[®] processed AM-produced Ti-6Al-4V components have shown significant improvements on performance. Our working hypothesis establishes that with the Extreme ISF[®] Process we are capable of reaching the notches and micro-notches at the surface and eliminate, or at least, round them; by reducing their depth and notch angle with the chemical assisted mechanical metal removal. Further experiments are on preparation.

REFERENCES

- [1] Santos LMS, Ferreira JAM, Jesus JS, Costa JM, Capela C. Fatigue behaviour of

- selective laser melting steel components. *Theoretical and Applied Fracture Mechanics*. 2016; 85: 9–15.
- [2] Wycisk E, Solbach A, Siddique S, Herzog D, Walther F, Emmelmann C. Effects of Defects in Laser Additive Manufactured Ti-6Al-4V on Fatigue Properties. *Physics Procedia* [Internet]. 2014; 56: 371–8. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S187538921400265X>
- [3] Johnson AS, Shao S, Shamsaei N, Thompson SM, Bian L. Microstructure, Fatigue Behavior, and Failure Mechanisms of Direct Laser-Deposited Inconel 718. *JOM* [Internet]. 2016; 69: 597–603. Available from: <http://link.springer.com/10.1007/s11837-016-2225-2>
- [4] Milewski JO. Additive Manufacturing of Metals: From Fundamental Technology to Rocket Nozzles, Medical Implants, and Custom Jewelry [Internet]. Springer International Publishing; 2017. (Springer Series in Materials Science). Available from: <https://books.google.com/books?id=XlsqDwAAQBAJ>
- [5] Bača A, Konečná R, Nicoletto G, Kunz L. Influence of Build Direction on the Fatigue Behaviour of Ti6Al4V Alloy Produced by Direct Metal Laser Sintering. *Materials Today: Proceedings*. 2016; 3(4): 522–5.
- [6] Spierings AB, Herres N, Levy G, Buchs C. Influence of the particle size distribution on surface quality and mechanical properties in additive manufactured stainless steel parts. *Rapid Prototyping Journal Special Issue: SFF 2010*. 2011; 17(3): 195–202.
- [7] Sun YY, Gulizia S, Oh CH, Fraser D, Leary M, Yang YF, et al. The Influence of As-Built Surface Conditions on Mechanical Properties of Ti-6Al-4V Additively Manufactured by Selective Electron Beam Melting. *JOM*. 2016; 68(3): 791–8.
- [8] Grimm T, Wiora G, Witt G. Characterization of typical surface effects in additive manufacturing with confocal microscopy. *Surface Topography: Metrology and Properties* [Internet]. 2015; 3(1): 014001. Available from: <http://stacks.iop.org/2051-672X/3/i=1/a=014001?key=crossref.c912a6d021eaa64a8bdfd607d8c4666e>
- [9] Pyka G, Kerckhofs G, Papantoniou I, Speirs M, Schrooten J, Wevers M. Surface roughness and morphology customization of additive manufactured open porous Ti6Al4V structures. *Materials*. 2013; 6(10): 4737–57.
- [10] Mahamood RM, Akinlabi ET. Effect of Laser Power on Surface Finish during Laser Metal Deposition Process. *Proceedings of the World Congress on Engineering and Computer Science*. 2014; II: 22–4.
- [11] Tumor IY, Thompson DC, Wood KL, Crawford RH. Characterization of surface fault patterns with application to a layered manufacturing process. *Journal of Manufacturing Systems* [Internet]. 1998 Jan 1 [cited 2017 Dec 1]; 17(1): 23–36. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0278612598800071>
- [12] Sidambe AT. Three dimensional surface topography characterization of the electron beam melted Ti6Al4V. *Metal Powder Report* [Internet]. 2017; 72(3): 200–5. Available from: <http://dx.doi.org/10.1016/j.mprp.2017.02.003>
- [13] Townsend A, Senin N, Blunt L, Leach RK, Taylor JS. Surface texture metrology for metal additive manufacturing: a review. *Precision Engineering* [Internet]. 2016; 46: 34–47. Available from: <http://dx.doi.org/10.1016/j.precisioneng.2016.06.001>
- [14] Nicoletto G. Directional and notch effects on the fatigue behavior of as-built DMLS Ti6Al4V. *International Journal of Fatigue* [Internet]. 2018 Jan 1 [cited 2017 Nov 28]; 106(August 2017): 124–31. Available from: <http://dx.doi.org/10.1016/j.ijfatigue.2017.10.004>
- [15] Nebiolo WP. Chemically Accelerated Vibratory Finishing of Aerospace Components. In: *Annual Aerospace Airline Plating and metal Finishing Forum*. 1996. p. 85–90.
- [16] REM. History of REM Surface Engineering [Internet]. [cited 2017 Oct 7]. Available from: <http://www.remchem.com/company/history/>
- [17] Michaud J. Materials Matter: Gear Surfaces and Operational Performance. *Gear Solutions* [Internet]. 2015 Dec; 18–9. Available from: http://www.gearsolutions.com/media/uploads/assets/PDF/Articles/Dec_15/1215-MM.pdf
- [18] Arvin J, Manesh A, Michaud M, Sroka G, Winkelmann L. The effect of chemically accelerated vibratory finishing on gear metrology. In: *AGMA 02FTM1*. 2002.
- [19] Michaud J. Materials Matter: Isotropic Superfinishing- *Gear Solutions Magazine*. *Gear Solutions Magazine* [Internet]. 2015

- Oct; 22–5. Available from:
<http://www.gearsolutions.com/article/detail/6604/materials-matter-isotropic-superfinishing>
- [20] Michaud J. Materials Matter: Additive Manufacturing: Challenges, Possibilities, and the Gear Industry. Gear Solutions Magazine [Internet]. 2017 Mar; 22–3. Available from:
<http://www.gearsolutions.com/article/detail/6775/materials-matter-additive-manufacturing-challenges-possibilities-and-the-gear-industry>
- [21] Diaz A, Winkelmann L, Michaud J, Terrazas C. Surface finishing and characterization of titanium additive manufacturing components: from rich to smooth surface. In: World PM2016 Proceedings. 2016.
- [22] Diaz A. ISF® Process of Additive Manufacturing Components: Towards the perfect surface finishing (post-processing) [Internet]. <https://www.linkedin.com/pulse/isf-process-additive-manufacturing-components-towards-agustin-diaz/>. 2016. Available from:
<https://www.linkedin.com/pulse/isf-process-additive-manufacturing-components-towards-agustin-diaz/>
- [23] Wright S. 3D printing titanium and the bin of broken dreams. 2015;(Part 3): 1–8. Available from:
<http://pencerw.com/feed/2015/3/15/3d-printing-titanium-and-the-bin-of-broken-dreams>
- [24] Wright S. A story of failure and success in metal AM: The reality of developing a titanium bike part. Metal AM. 2015; 1(3): 41–5.
- [25] Witkin D, Patel D, Helvajian H, Diaz A. Surface Treatment of Powder Bed Fusion Additive Manufactured Metals for Improved Fatigue Life. Journal of Materials Engineering and Performance. 2018; Submitted.
- [26] Witkin D, Patel D, Helvajian H, Diaz A. Surface Treatment of Powder Bed Fusion Additive Manufactured Metals for Improved Fatigue Life. MS&T 2017. 2017;

Shape Adaptive Grinding of Additively Manufactured Cranial Implants on a Robotic Platform

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INTRODUCTION

Additive Manufacturing in recent years has become a viable rapid prototyping technology, notably in the aerospace and medical sectors. A vast improvement to the range of available printing media has meant more and more complex freeform geometries can be made. However, AM parts are known to have large form deviations from the nominal CAD designs and surface roughness. The challenge for this research was to be able to post-process an AM cranial implant straight from the printer to a precision polished surface.

Shape Adaptive Grinding (SAG) was developed by Zeeko Ltd as a novel process for precision grinding of complex freeform surfaces [1]. The SAG process is a hybrid process that sits between grinding and polishing. Typical applications for the SAG process include the grinding and finishing of optical surfaces and precision finished moulds.

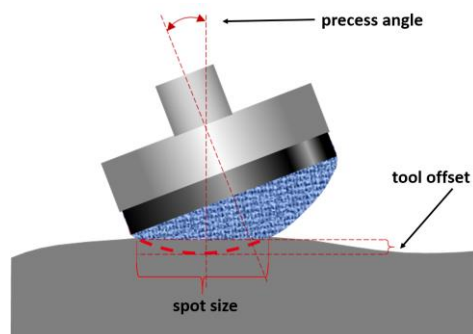


FIGURE 1. SAG tool contacting freeform surface.

The SAG tooling was designed to be 'semi-elastic' and consists of a metal supporting stem, an elastic rubber layer, and finally an abrasive layer[2]. This abrasive layer contains abrasive particles that are held together using a bond material. Typically, the abrasive particles are

diamond and range from 3 μ m to 125 μ m in grain size - this gives SAG the versatility required to take an additively manufactured part straight from the printer all the way to an optical surface finish.

Robotic arms are widely used in manufacturing applications such as welding, component handling, and various material removal processes. It is common for manual processes to be automated by robotic integration, potentially gaining accuracy, repeatability, and throughput. However, modern robot arms can offer a versatile and cost-effective platform for a multitude of processes otherwise restricted to high-cost, precision CNC-machines, even at the expense of some accuracy.

METHODOLOGY

AM Cranial Implants

The initial conditions of the AM Cranial Implant are shown in FIGURE 2. The surface is covered in excess powder and the remains of support structures (up to 1mm proud of the underlying surface) from the AM process.



FIGURE 2. Initial Condition of AM Cranial Implant.

The implant is very thin for an AM component (nominally <1mm) so stress in the metal is a

likely source of the deviation between the nominal CAD and the underlying form of the component. The required surface roughness of the implant was to be sub-350nm R_a .

The Cranial implant was mounted to a fixture using NexGenOptical blocking wax – the holding strength of the wax was suitable for this application due to the shear forces applied during polishing. Only a rough visual-alignment of the part could be made when placing the implant into the robot-enclosure, so probing the surface to locate its position and orientation in the robot user-frame was critical.

Tool Path generation

ZephyrCAM polishing software, developed by Zeeko Ltd, was used to generate all probing and polishing tool paths.

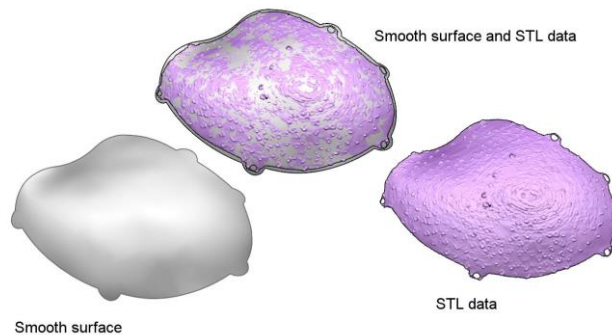


FIGURE 3. Smoothed surface vs GOM-scan data.

Each cranial implant was measured using a GOM scanner. The point-cloud measured data was smoothed to reduce the impact of the surface artefacts and used to generate an updated NURBS surface (FIGURE 3). The AM component deviated from the nominal CAD by 100-300µm across the surface. The excess material and support artefacts are also evident.

Polishing Process

The SAG process was conducted on a Fanuc M10iA robot, with an R30iB controller, and a Suhner UAL 23-RF spindle mounted to the end-effector. Multiple SAG tools of 10mm radius were used with different diamond-abrasive pads: 125µm Nickel Bonded, 40µm Nickel Bonded, 9µm Nickel Bonded and 3µm Resin Bonded.

The AM part was probed to position and orientate the part within the robot user frame. A probe-tool was made using a NovaTech F259UF0H0 load cell mounted onto a spigot with a conic delrin cap.

This was configured for touch-trigger type probing.

Roughness measurements were taken using a Taylor-Hobson CCI white-light interferometer.

RESULTS AND SUMMARY

Probing

Probing was performed at multiple grid positions projected onto the CAD surface. For each position, the probe-tool was placed at an offset above the surface and orientated normal to the surface. The probe-tool was then moved slowly towards the surface along the surface normal until the load cell reached a certain threshold.

Only the center two thirds of the AM parts could be used for probing due to limited space within the enclosure – even so, the data obtained would be sufficient to calculate the position and orientation of the component.

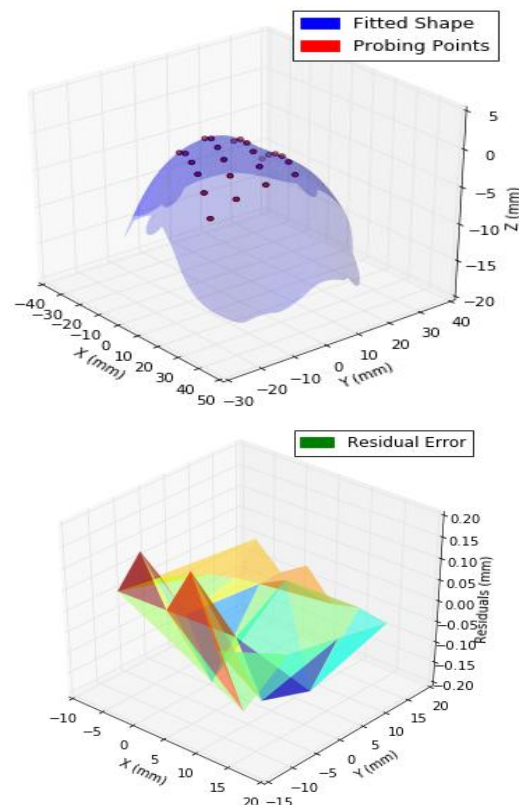


FIGURE 4. Probing data fitting and residuals.

The initial probe performed after visual-alignment of the component in the enclosure. This probing

data was fitted to the nominal CAD surface in software to establish the rough position and orientation of the implant. Subsequent probing toolpaths were compensated with this information to vastly improve positional accuracy, and to obtain more accurate probe data.

FIGURE 4 shows the fitting of probe data to the CAD surface after multiple iterations of probing, with a peak-to-valley of the residual error of 300um. This was satisfactory given the accuracy of the AM component and the accuracy required by the SAG process.

Polishing Process

Each polishing toolpath was a raster pattern, with each subsequent toolpath orientated at 90° to the previous toolpath – this was to make it easier to monitor the removal as well as aiding in removing the raster-tracks from previous runs. The spacing between tracks was 500um and reduced to 200um for the small-abrasive (9um and 3um grit size) tools. Surface feed was set at 400mm/min and reduced to 200mm/min for the small-abrasive tools. The spindle speed was set at the minimum of 2500rpm.

The polishing tool was positioned at a precess angle of 25° to the surface (**Error! Reference source not found.**) to provide a satisfactorily high removal rate of material while not colliding with the restrictive containment unit.

During processing with the 125um tool, the tool was initially offset 1mm above the target surface to avoid damaging the abrasive pad when attacking the support structure artefacts. This offset was reduced in steps of 200um for subsequent toolpaths until the nominal surface had been reached and the tooling was changed to the 40um, 9um, and um tools sequentially.

The AM parts were ground and polished using the four tools of progressively reduced grit size in order to reduce the surface roughness to specification without removing too much material. Cumulative processing times for each tool were: 125um Nickel Bond - 5 hours 19 minutes, 40um Nickel Bond - 1 hour 9 minutes, 9um Nickel Bond - 1 hour 11 minutes, and 3um Resin Bond - 1 hour 15 minutes.



FIGURE 5. Implant after 40um SAG process.

Measurements

The implant after processing with the 125um and 40um tools can be seen in FIGURE 5 – raster marks and residual pits from the AM support structures are still apparent. Roughness measurements taken after polishing with the 40um-tool showed that an average R_a of 320nm was achieved.

The AM cranial implant after further polishing with the 9um and 3um tools can be seen in FIGURE 6. Roughness measurements gave an average R_a of 180nm, with some areas as good as 83.86nm. The 3um tool was seen to not improve the surface roughness by much due to the remaining 9um tool raster-marks being too dominant.



FIGURE 6. The final AM Cranial Implant

Conclusions

The viability of polishing an AM cranial implant using the SAG process on a robotic-arm was shown, with the target roughness being met.

Pitting from the AM support structures still remained in a localised area at the centre of the implant. This is likely due to there still being a mismatch with the CAD file used in generating the toolpaths. Additional processing with the large-abrasive tools in the earlier process steps will also aid in removing these artefacts.

The polishing parameters and process times have potential to be improved dramatically at all stages. A cautious approach had to be taken due to a limited number of test parts and lack of knowledge about the effectiveness of the SAG process on a robotic platform.

REFERENCES

- [1] Beaucamp A, Namba Y, Charlton P. Process mechanism in shape adaptive grinding (SAG). CIRP Annals. 2015 Jan 1;64(1):305-8.
- [2] Beaucamp A, Namba Y. Shape adaptive grinding (SAG): a novel fabrication method for freeform optical molds. In Optical Fabrication and Testing 2014 Jun 22 (pp. OTu3B-5). Optical Society of America.

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